FUNDAMENTAL INTERRELATIONSHIPS BETWEEN CERTAIN SOLUBLE SALTS AND SOIL COLLOIDS

BY

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INTRODUCTION

While engaged in an extensive investigation of the physiological effects of $NaCl$, Na_2SO_4 and Na_2CO_3 on crop plants as grown in the Davis clay loam, in cylinders, under field conditions, the writer observed that the soil to which the salts had been previously applied became so impervious during the course of the experiment as to retard markedly the rate of percolation. So pronounced was this effect that during the winter and early spring months all of the salt-treated soils were continuously covered with standing water. The appearance of this striking modification in the permeability of the soil to water in the salt-treated soils, together with the inferior cultivating qualities exhibited by them, impressed us as evidence of the fact that the salt treatments under the field conditions of the experiment had effected a fundamental change in the physical constitution of the soil. The occurrence and nature of this change and its relation to soil colloids, interior surface, and other properties of soils, form the considerations with which this paper is chiefly concerned.

Just such an effect on the physical condition of the soil as described above had been anticipated as the normal result of adding Na_2CO_3 to the soil, for this salt has generally been conceded, by soil experts, to be an active deflocculating agent. But

to find, on the other hand, that a similar state of diffusion existed in the soils to which NaCl or Na_2SO_4 had been added appeared wholly inexplicable in the light of the prevailing conception of these salts as agents capable of producing flocculation in the soil colloids. However, this apparent contradiction of well-established facts brought out by the field observations becomes more intelligible as the accumulating data define more clearly the conditions necessary to produce the remarkable effects observed. Thus it has been demonstrated, not only in the field but also in the laboratory, that the removal from the soil by water of NaCl or Na_2SO_4, together with the water-soluble products of their chemical reaction with the soil constituents, either wholly or in part, is the initial step in creating a condition favorable for the diffusion of the soil colloids and possibly for the formation of new colloidal matter. Therefore the net result of salt application to and subsequent washing of a soil is to render the soil comparatively impervious and to injure seriously its physical condition. The leaching out of added Na_2CO_3 from the soil also presents some interesting phenomena, which are discussed below.

Although the alteration in the physical condition of the soil was first observed by the writer as purely incidental to an investigation primarily designed to ascertain the toxicity limits of the common alkali salts for crop plants, yet it has proved, at least in the case at hand, a most perplexing factor in the production of crops. Our experience would lead us to believe that these after-effects of salt treatments, which appear during the course of leaching the salts from the soil, would have some application to the management of alkali lands, and perhaps some significance with respect to fertilizer treatments. However, the literature on these subjects, with a few exceptions, seems quite devoid of any pertinent reference to the possible importance in these problems of the factor discussed above.

A survey of the literature concerning soils reveals the chief exceptions just mentioned in the following important contributions to this subject. Thus, a brief but significant chapter, "Veränderung der Durchlässigkeit durch Auswaschen der Salze," by Adolph Mayer,[1] records a somewhat sudden reduction

[1] Forschungen auf dem Gebiete der Agrikultur-Physik, vol. 2, 1879. p. 251.

in the permeability of a soil when NaOH is washed from it. A similar experiment performed by Mayer with sodium phosphate was not accompanied with the sudden reduction in permeability of the soil as was noted when NaOH was washed from the soil. Likewise the washing out of lime-water produced no marked effect on the rate of percolation, but the leaching out of added NaCl, either with pure water or with lime-water, reduced percolation to a minimum. Mayer ascribes the poor physical condition of drained sea-shore lands to the washing out of the salt, and significantly remarks that this effect, which frequently appears in the second year, is probably more injurious to crop plants than the toxicity of the salt itself.

Van Bemmelen[2] in his classical researches on colloids has also observed a similar decrease in the rate of percolation when loosely bound salts are washed from clays or from the hydrated oxides of tin, silica, and manganese. Moreover, he noted that these colloids, when subjected to salt treatments followed by leaching with water, invariably exhibited a high degree of diffusion upon suspension in water for a second time. He further asserts that this process can be indefinitely repeated by alternately adding to and washing salt from the colloids. The colloidal particles, as remarked by Van Bemmelen, become so exceedingly small, during the process of washing salts from them, as to pass through the filter paper.

Warington[3] also refers in a general way to the appearance of somewhat similar phenomena when soils, previously treated with acids, are washed with water.

It would appear, with the above exceptions, that those who have studied absorption, adsorption, or other physico-chemical effects of salts on soils, have failed to recognize the existence of any relation between the washing out of salts and the subsequent condition of the soil. In fact, Hall and Morison[4] assert that the flocculating effect of salt solutions on kaolin are reversible, that is to say, upon the removal of the added salt the kaolin resumes the original condition of diffusion.

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[2] Journ. prakt. Chem., 2nd ser., vol. 23, p. 388, 1881.

[3] Physical Properties of Soil (Cambridge Univ. Press, 1900), p. 30.

[4] Journ. Agri. Sci., vol. 2, p. 244, 1907.

That these earlier findings have a greater significance in agricultural practice than was formerly attributed to them be. comes very evident when the practical phase is attempted of cropping the diffused, salt-treated, water-washed soils in our cylinders. Heretofore, the residual effects left upon clays and clay soils after salts have been washed from them have been chiefly considered in connection with their application to the ceramic industry, and have been largely omitted from consideration by those dealing with soils.

Since the striking soil behavior under discussion was first observed by us, as above explained, in crop cylinder experiments, it appears desirable to introduce here a brief description of these experiments.

The Cylinder Experiment on the Physiological Effects of NaCl, Na₂SO₄ and Na₂CO₃ on Crop Plants

The cylinders used in this experiment are of galvanized iron. open at both ends, coated inside and out with asphaltum, and are fourteen inches in diameter and five feet long. They were placed, during September, 1913, in a clay loam soil at Davis. California, by digging holes to the depth of five feet. During the progress of digging the holes the soil from each foot was carefully removed and set aside separately, thus permitting the cylinders to be refilled with the soil layers in the same order as they exist naturally.

The soils within the cylinders were then supplied with varying percentages of the three sodium salts, NaCl, Na₂SO₄, and Na₂CO₃. It seemed a difficult task to secure a satisfactory mixture of the salts with the soil already in the cylinders, and it was therefore deemed wise to apply the salts to the surface of the soils by means of a solution containing the weighed quantity of salt in 8800 cc. of distilled water. Accordingly, each cylinder received the same quantity of water, but of a different salt concentration. In addition to the salts some of the soils also received other treatments which, together with the salt treatments. are detailed in the following chart. The quantities of salts were

calculated and applied on the basis of percentage of weight of the five-foot column of soil in every cylinder.

As mentioned above, all of the salt-treated soils developed, every indication of a thoroughly diffused condition. As a result, percolation through the treated cylinders practically ceased, so that the rain-water collected in the two-inch cylinder rim and remained so persistently as to prove seriously detrimental to the
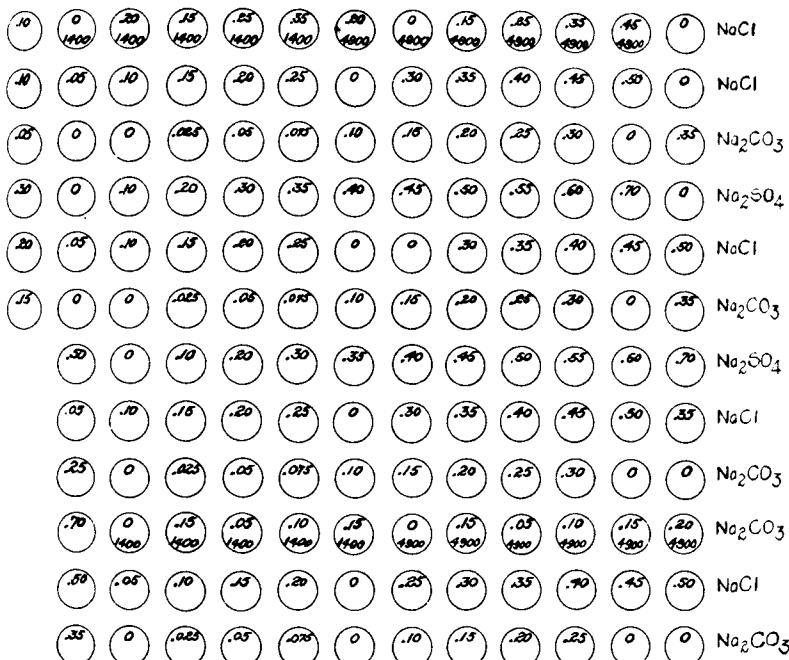

Fig. 1.   The Salt and Manure Applications to the Soil in the
Cylinders at Davis.

The upper figures refer to the percentages of salts in the 5-foot column of soil. The lower figures refer to the grams of barnyard manure added. In row 1, no. 1 contains Na_2SO_4 instead of NaCl. In row 10, no. 2 likewise contains Na_2SO_4 instead of Na_2CO_3.

growth of crops. As a final measure, holes were opened down through the soil columns to provide drainage. In sharp contrast with the treated soils, even immediately after heavy rain-storms, no standing water was ever observed on the control soils, and the splendid growth of the crops planted on them showed a congenial condition for crop development. Both the winters of

1913–14 and 1914–15 were accompanied with similar manifestations of the extreme retentiveness and imperviousness of the salt-treated soils.

As previously remarked, all of the check soils responded readily to cultivation and excellent seed beds were easily prepared, while the soils to which NaCl and Na_2SO_4 had been added were in an unworkable condition. A crust, an inch or so in thickness, formed as soon as the surface dried, and was so hard that even heavy tools made but little impression on it. Just below the crust the soil was far too wet for plant roots and resembled putty in consistency. Contrary to expectations, the soils treated with Na_2CO_3 exhibited better cultivating qualities than the soils receiving the other salts, but inferior to those of the control soils.

With a view to obtaining further information concerning the great dissimilarity between the control soils and the salt-treated soils, it seemed wise to examine some of the surface water standing in the cylinders as well as the soil in contact therewith. These proved to contain but mere traces of any salts. Of next importance a study of the vertical distribution of the salts in the cylinders disclosed the fact that the first few inches of soil contained relatively small quantities of the salts, the first foot more, the second still more, and the third foot most salt. From these results it was concluded that the addition of NaCl or Na_2SO_4 to a soil and subsequently washing the added salt, or at least part of it, from the soil with water, produces a high degree of diffusion in the soil colloids. Moreover, this alteration in diffusion was accompanied with proportional changes in the other physical characteristics of the soil. These conclusions based on our field experience were soon verified by laboratory experiments.

LABORATORY EXPERIMENTS REPRODUCING FIELD OBSERVATIONS

It has been found that the field conditions can be readily reproduced in the laboratory. Thus a simple procedure, illustrating qualitatively the lessened percolation, is to place 10 grams or more of soil in a filter paper in a funnel, adding thereto either NaCl or Na_2SO_4 as a solid or in a water solution, and then wash-

ing the soil practically free of salt, meanwhile washing with pure water a similar portion of soil from which the salt has been omitted to serve as a control. The difference in the rate of percolation of the two soils has proved to be sufficiently great to be easily discernible even in the case of sandy soils. Frequently
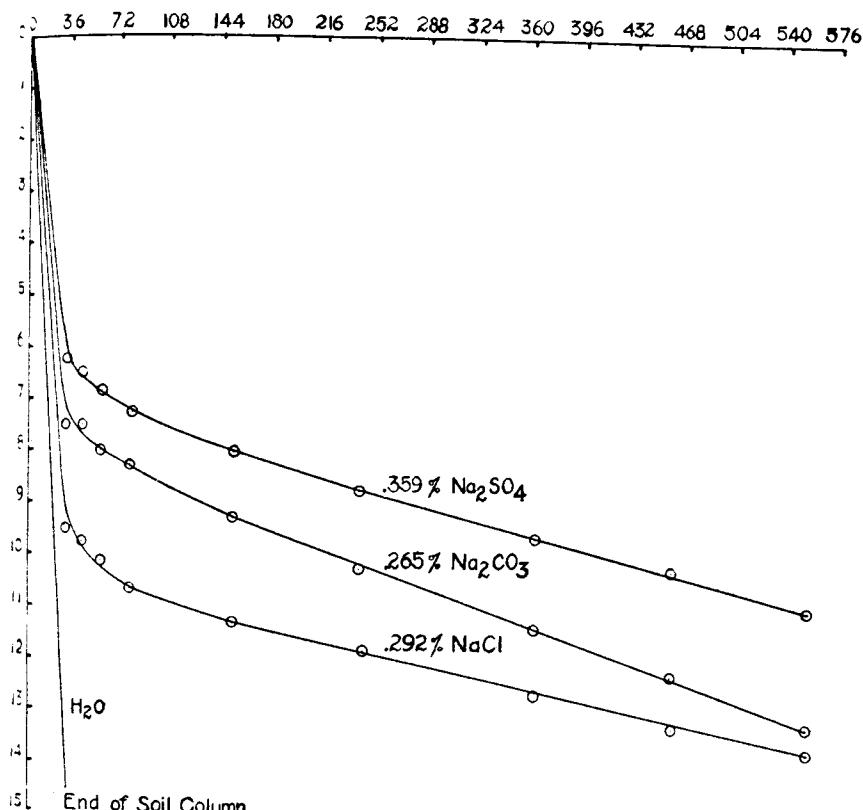
Fig. 2. Curves Representing the Downward Movement of Water Through the Davis Soil to which Salts Have Been Added.

The penetration of the water downward in the soil column is expressed in inches by the ordinates, while the abscissas represent the time of observations in hours.

the fine material mentioned by Van Bemmelen and Warington appears in the percolate.

It has also been found possible to simulate fairly the conditions existing in the field cylinders by means of glass tubes care-

fully filled with the Davis clay loam to which chemically equiva-
lent salt solutions were added, much in the same manner as the
salt applications were made to the cylinder soils. A constant
head of water was then carefully maintained in the tubes. The
downward movement of the water was observed from time to
time and is graphically portrayed in Figure 2.

From the curves in it it is very apparent that the influence of
these salt additions, accompanied by subsequent surface applica-
tions of water to the soil, has been to retard, markedly, the down-
ward movement of the water through the soil. In less than 33
hours the water had penetrated the entire 14½ inches of soil in
the control tube, while at the end of 552 hours, under a constant
head of three inches, the maximum distance reached in any of
the salt-treated soils was 13¾ inches in the case of the soil
receiving NaCl, followed by 13¼ inches in the Na$_2$CO$_3$ soil, and
but 11 inches in the soil to which Na$_2$SO$_4$ had been added. At
the expiration of 56 days no percolation had occurred, though
the entire soil columns were moist. The total absence of percola-
tion in the salt-treated soils was attributed to the growth of algae
in the tubes.

To test further the points under consideration, a second series
was prepared to study the rates of percolation through Davis
clay loam to which salts had been added in various ways. The
results of this experiment are embodied in Table I.

In the above experiment the chemically equivalent quantities
of salts were mixed uniformly with the dry soil before placing
the mixture in the paraffine-coated brass percolation tubes, except
in the case of Nos. 12, 13, and 14, through which salt solutions
were passed of a strength (calculated on the basis of a previously
determined water-holding power of the soil) to give compara-
tively equal quantities of salts with those soils receiving the dry
salts. A head of one to two inches was carefully maintained on
the soil in all the tubes throughout the experiment.

The results recorded in the foregoing table fully corroborate
the field experience. Thus, the average rate of percolation of
the check soil was 1.59 cc. per hour, while that of the soil to
which NaCl has been added was reduced to .19 cc. per hour. The
percolation through the other two soils which received solid

TABLE I

RATES OF PERCOLATION THROUGH SOILS RECEIVING VARIOUS SALT TREATMENTS

	Height of Soil Column	1st Salt	Per cent of 1st Salt	2nd Salt	Per cent of 2nd Salt	This column omitted from all averages	First three			Second three			Average of last six Observations	Average of 2nd, 3d, and 4th Observations	Average of 5th, 6th, and 7th Observations
						8.5 Oct. 15	**59** Oct. 21	**98** Oct. 26	**90** Oct. 30	**124** Nov. 4	**114** Nov. 9	**52** Nov. 11			
1	19.5 cm.	....	....	....	....	4.11	2.00	1.43	1.81	1.17	1.53	1.61	1.59	....	....
3	19.5 cm.	NaCl	.200	....	....	1.17	.23	.21	.24	.14	.18	.19	.19	....	....
4	19.5 cm.	Na₂SO₄	.246	....	....	.70	.35	.30	.33	.22	.28	.31	.31	....	....
5	19.5 cm.	Na₂CO₃	.183	....	....	.82	.47	.40	.44	.27	.32	.35	.37	....	....
6	19.5 cm.	NaCl	.200	CaSO₄, 2H₂O	.10	.94	.44	.38	.44	.27	.32	.36	.36	....	....
7	19.5 cm.	Na₂SO₄	.246	CaSO₄, 2H₂O	.10	1.20	.64	.54	.62	.40	.51	.54	.54	....	....
8	19.5 cm.	Na₂CO₃	.183	CaSO₄, 2H₂O	.10	1.76	.90	.74	.80	.49	.57	.58	.68	....	....
9	19.5 cm.	Nacl	.200	CaCO₃	.20	1.17	.54	.40	.47	.28	.34	.36	.39	....	....
10	19.5 cm.	Na₂SO₄	.246	CaCO₃	.20	1.53	.73	.56	.71	.44	.57	.60	.60	....	....
11	19.5 cm.	Na₂CO₃	.183	CaCO₃	.20	1.41	.61	.56	.66	.40	.50	.53	.54	....	....
12	19.5 cm.	Percolated solution of NaCl		6.96 gr. salt / 1000 cc. H₂O		7.29	2.45	1.73	1.66	1.10*	.57	.35	1.30	1.94	.67
13	19.5 cm.	Percolated solution of Na₂SO₄		8.57 gr. salt / 1000 cc. H₂O		7 05	3.05	2.29	1.94	1.03	.34	.21	1.47	2.42	.52
14	19.5 cm.	Percolated solution of Na₂CO₃		6.37 gr. salt / 1000 cc. H₂O		4.70	1.18	1.00	1.05	.89	.73	.61	.90	1.07	.74
15	19.5 cm.	....	....	CaSO₄, 2H₂O	.10	4.82	3.05	2.04	2.50	1.71	2.15	2.40	2.31	....	....
16	19.5 cm.	....	....	CaCO₃	.20	4.58	2.28	1.53	2.22	1.45	1.84	1.92	1.87	....	....

* At this point an immediate retardation of percolation is noted, due to the substitution of distilled water for the salt solution. The figure *1.66* for No. 12 on Oct. 30, is slightly low due to an oversight in the measurement of the percolate.

Na_2SO_4 and Na_2CO_3 was also decidedly reduced, as shown by the respective percolation rates of .31 cc. and .37 cc. per hour. In significant contrast thereto, the maintenance of a comparatively uniform salt content in the soil column, produced by substituting solutions of the salts for the distilled water as in the case of Nos. 12, 13, and 14, creates a favorable condition for percolation, except in No. 14, which received Na_2CO_3. In this case percolation averaged a rate of 1.07 cc. per hour, which was less than the control, but three times that of the soil receiving Na_2CO_3 and distilled water. It is of interest to note the immediate depression in the rate of percolation when distilled water is used instead of the salt solutions of Nos. 12, 13, and 14. Eventually the rate of percolation from these soils under applications of distilled water approached that of the soils originally treated with salts and which in addition had received only distilled water throughout the experiment.

Another percolation experiment, arranged somewhat similarly to the preceding, demonstrated that the relative position of the salt in the soil column, or the manner of adding it, had little or no influence on the depressing effect noted on percolation. It was further observed that a soil, the percolation rate of which had been diminished through the agency of NaCl and H_2O applications, failed to recover its original rate of percolation even when a solution of that salt was applied for the second time.

The general trend of the results thus far secured is in accord with Beeson's observations,[5] in which he recorded a delayed absorption of water by soils containing sodium salts as well as a pronounced retarding of percolation through soils to which various salts had been added. Like many other investigators who have observed similar effects resulting from salt treatments, Beeson failed to recognize any connection between the physical condition of the soil and the removal of the salt, but attributed the peculiar changes observed in the soil to surface-tension phenomena, or other alterations in the physical properties of the liquid phase, or, as some investigators are inclined to believe, to a shifting of the soil particles to new positions through the influence of the added salt. Undoubtedly a movement of soil

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[5] Journ. Am. Chem. Soc., vol. 29, p. 620, 1897.

particles does occur when salts are added to soils, but under the conditions obtaining in many of the experiments described in the literature it would seem highly improbable that enough of the added salt remains in contact with the soil to bring about such a movement of the particles. In our experience, the removal of the salt creates among the soil particles a new adjustment which seems of greater importance than that effected by the addition of the salt. Furthermore, if our laboratory experience is properly applicable to field conditions, it would seem of greater advantage to apply $CaCO_3$ rather than $CaSO_4$ when draining soils containing NaCl and Na_2SO_4, the reverse being apparently true in case of soils impregnated with Na_2CO_3.

LABORATORY INVESTIGATIONS OF THE CAUSES OF SALT EFFECTS ON SOILS

The laboratory studies herein reported have been purposely designed to throw some light on the possible causes contributing to the above-noted effects of salts on soils, or at least to ascertain if a relationship exists between the formation of these peculiar physical conditions and the simultaneous occurrence of certain other events. Certain well-known theoretical considerations, reinforced by concrete laboratory experience, have directed the attempts to locate these fundamental causes into three well-defined channels. The first of these is based on an assumption that the salt-and-water treatments have actually increased the quantity of the colloidal matter of the soil. It involves necessarily a study of the soil itself and of the amount and degree of diffusion of the colloidal matter therein contained. The second line of reasoning connects the increase of calcium and magnesium in the percolate from the salt-treated soils, and the absorption of sodium, with the appearance of conditions suitable for the formation of new colloidal matter, as well as with favoring the extreme diffusion of that already present. The third consideration ascribes the diffused condition of the soil colloids to the presence of a small quantity of OH-ions in the soil solution. It requires the theoretical assumption that these ions are associated in some manner with the absorption of sodium. Although these

three lines of argument, as outlined, may be closely allied or even parallel, yet in view of our work they seem sufficiently well defined to warrant a separate discussion of each.

At the outset it may be said that it has been extremely difficult to find appropriate and reliable methods of attacking this problem. Certainly opportunity is not lacking for future investigations to perfect accurate methods for definitely measuring certain soil properties or soil constants, which are discussed below. The Davis clay-loam soil was used throughout the following experiments, except as otherwise noted. The designation NaCl + H₂O used before the word *soil* signifies that the soil was treated with from 0.2 to 0.5 per cent of NaCl, most or all of which, together with the soluble salts formed, has been subsequently leached from the soil with water. It must be added that a quantity of Davis clay-loam soil was given the same amount of washing with water to serve as a control soil, and hereafter will be referred to as H₂O soil. A comparison of the H₂O soil with unwashed Davis soil disclosed no important differences.

Some Physico-Chemical Observations on the Salt-Treated, Water-Washed Soil

It seemed reasonable to expect that a study of the NaCl + H₂O soil itself would reflect, in some degree, the causes contributing to the pronounced imperviousness of such soils. Therefore, as an introduction to this subject, determinations were made of the suspended matter derived from soils which have been subjected to various treatments, and they appear in Table II. The soils and suspending media were placed together in tall hydrometer jars, and were thoroughly shaken for 45 minutes. After standing undisturbed for eighteen hours, aliquot portions of the suspensions were removed by means of a pipette, evaporated to dryness in platinum dishes, dried at 110° C, and weighed.

The data reported in Table II confirm by an entirely different procedure the original belief with respect to the intensity of the diffusion of the colloids of the salt-treated, water-washed soils. Under the conditions of the experiment 40 grams of normal soil yielded 0.310 grams of suspended matter, while 40 grams of

TABLE II

SUSPENDED MATTER IN SOILS WHICH HAVE RECEIVED VARIOUS TREATMENTS

No.	Davis Soil	Previous Soil Treatment	Suspending Medium	Weight of Suspended Matter-grs.	Per cent of Suspended Matter in soil
1	40 grs.	Washed with distilled water	H_2O	.3100	.77
2	40 grs.	Boiled in H_2O	H_2O	2.5075	6.27
3	40 grs.	.290 grs. of NaCl washed out	H_2O	2.9555	7.39
4	40 grs.	....	$N/50$ Na_2CO_3	.2665	.66
5	40 grs.	....	$N/50$ NaOH	2.7975	6.99

NaCl $+$ H_2O soil yielded 2.9555 grams, or nearly ten times the amount of suspended matter found in the untreated soil. It is an interesting coincidence that the rate of percolation previously shown for the untreated soil is almost ten times that for soil to which NaCl has been added and subsequently leached out. It may be properly inferred from this that percolation varies inversely as the degree of diffusion, though our present knowledge does not indicate a relation capable of expression in simple mathematical terms. Furthermore, the inadequacies of the method employed to secure the data in Table II make it impossible to express a positive view with reference to the quantity of colloids in the soils tested, but it is evident that the colloidal matter present is in a much higher state of diffusion in certain of the soils than in the control H_2O soil. The three treatments, boiling the soil in water, suspending it in NaOH of certain concentrations. and leaching added NaCl from it. produce approximately the same degree of diffusion in the soil colloids, as indicated by the similarity in the results of the quantitative estimations of the suspended matter derived from soils so treated. This agreement in the behavior of the soils receiving the different treatments suggests a similarity or possible relationship between the processes by which these treatments affect the soil or soil colloids. Boiling the soil in water has been assumed by soil physicists to disintegrate the colloidal aggregates. If this be the case and no new colloidal substances are formed by this procedure, then the similarity in colloidal content of the boiled soil and the salt-treated, water-washed soil militates against the sup-

position that the latter treatment has increased the colloidal matter of the soil. On the other hand, boiling the soil in water may bring about a more profound change in the physical condition of the soil than was formerly attributed to it by soil physicists. Some data withheld from publication at this time indicate that the effect of the boiling treatment is of a different nature from that of the salt-and-water treatment, though the soils receiving the two different treatments yield about the same quantity of colloidal matter. On the other hand, the similarity of the colloidal contents of the boiled soil and the soil suspended in NaOH admits of a more plausible explanation on the basis of NaOH as a deflocculating agent.

It was thought that the quantitative data reported above might show sufficient dissimilarity to indicate an actual increase in the soil colloids, but a second series of determinations, reported in a later paragraph, are somewhat contradictory to the above, in that the boiled soil yields a suspension slightly richer in colloidal matter than that derived from a $NaCl + H_2O$ soil. This point, however, deserves more investigation before a final conclusion is reached.

In the light of certain theories more properly discussed in connection with the third hypothesis, it is of great interest to note the general similarity between the $NaCl + H_2O$ soil when suspended in H_2O and the normal soil when suspended in NaOH. One might infer that this peculiar agreement in the behavior of the soils in response to two widely different treatments is not accidental. It is also to be observed further that the data under consideration indicates that NaOH and Na_2CO_3 are not productive of like results on soil suspensions.

The failure of the suspension method to secure trustworthy results on the quantity of colloidal matter present prompted the adoption of other means for this purpose. But thus far the determination of the hygroscopic coefficient and the dye-adsorption capacity have given negative results, in that they have not indicated any increase in the total interior surface of the soils which have been subjected to the salt treatments. From a theoretical consideration, a soil rich in colloids, or containing colloids in a high state of diffusion, should expose more interior

surface for the deposition of hygroscopic moisture and for dye adsorption, and since these phenomena are presumably direct functions of surface the soils under observation should therefore register increased hygroscopicity and dye adsorption. The findings to the contrary cast some doubt on the validity of these measurements as a reflection of the quantity of colloidal matter present or its degree of diffusion. A third method suggests itself, that developed by Mitscherlich,[6] to study the interior surface through energy exchanges when the soil is moistened with water, but this has not as yet been tried.

The use of the centrifugal machine as employed by Briggs and McLane[7] to ascertain the moisture equivalent of soils in the study of the salt-treated, water-washed soils, has yielded some highly satisfactory results which will be reported in a future paper. The method proposed by Lynde and Dupré[8] for estimating the capillary powers of soils has not proven entirely satisfactory in our hands, when employed for investigating the properties of the salt-treated soils.

It was further questioned whether the physical condition of the soil had been permanently changed or whether the injured soil would completely recover its original condition in response to a second addition of NaCl. Such a supposition naturally implies that some of the reactions involved in producing the increased diffusion partake of the nature of reversible reactions. In order to test this point from a chemical standpoint, it would be necessary to treat the injured soil with its own percolate. Work of this character is reported under the second series of experiments. In this connection, however, the effects of the added salts were considered chiefly in their physical aspects, and accordingly the following experiment was performed: Three grams of NaCl + H_2O soil were suspended in 10 cc. of NaCl solutions of various concentrations in test-tubes. The time required to clear the supernatant liquid denoted the effect of the NaCl. A similar comparative series with H_2O soil was also prepared. The results are given in Table III.

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[6] Bodenkunde für Land- und Forstwirte, p. 51.

[7] U. S. Dept. Agr., Bur. of Soils, Bull. 45.

[8] Journ. Amer. Soc. Agron., vol. 5, no. 2, p. 107, 1913.

TABLE III

EFFECT OF SECOND ADDITION OF NaCl ON TIME REQUIRED TO CLEAR SUSPENSIONS OF NaCl+ H₂O SOIL AND H₂O SOIL

No.	Soil	Previous Treatment	Concentration of NaCl as Suspending Medium	Time Required to Clear Suspension
1	3 grs.	NaCl washed out	....	Almost clear after 600 hrs.
2	3 grs.	NaCl washed out	N/1000	Almost clear after 600 hrs.
3	3 grs.	NaCl washed out	N/500	Almost clear after 600 hrs.
4	3 grs.	NaCl washed out	N/250	Clear after 600 hrs.
5	3 grs.	NaCl washed out	N/100	Clear after 360 hrs.
6	3 grs.	NaCl washed out	N/50	Clear after 20 hrs.
7	3 grs.	H₂O washed	....	Clear after 164 hrs.
8	3 grs.	H₂O washed	N/1000	Clear after 140 hrs.
9	3 grs.	H₂O washed	N/500	Clear after 117 hrs
10	3 grs.	H₂O washed	N/250	Clear after 53 hrs.
11	3 grs.	H₂O washed	N/100	Clear after 1 hr.
12	3 grs.	H₂O washed	N/50	Clear after 1½ hr.
13	3 grs.	....	....	Clear after 140 hrs.

The results of this experiment seemed of sufficient interest to warrant a repetition of the work on a larger scale. Accordingly the following experiment was prepared, much in the same manner as the above, but using 25 grams of soil, 250 cc. of solution, and 250 cc. graduates, instead of test tubes. In this case the weight of the suspended matter was also determined after the mixtures had stood undisturbed for three days. A photograph of this series taken two days after the final shaking is shown (Figure 3).
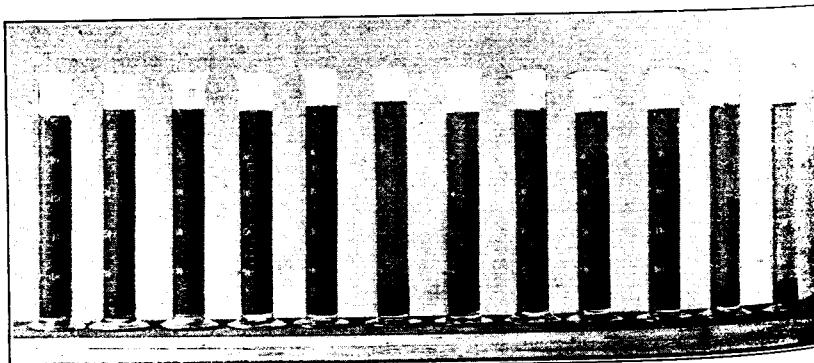

Fig. 3. A Photograph of the Suspensions Described in Table IV

The graduates containing the suspensions as shown in Figure 3 correspond, from left to right, to the Nos. 1 to 12, inclusive, of Table IV.

TABLE IV

EFFECT OF SECOND ADDITION OF NaCl ON THE AMOUNTS OF SUSPENDED MATTER
FROM NaCl + H₂O SOIL AND H₂O SOIL

No.	Soil	Previous Treatment	Concentration of NaCl Suspending Solution	Cc. of Suspending Medium	Weight of Suspended Matter	Per cent of Suspended Matter on Dry Soil
1	25 grs.	NaCl washed out	....	250	.8345 grs.	3.33
2	25 grs.	NaCl washed out	N/1000	250	.6375	2.55
3	25 grs.	NaCl washed out	N/500	250	.5615	2.36
4	25 grs.	NaCl washed out	N/250	250	.4570	1.82
5	25 grs.	NaCl washed out	N/100	250	.2305	.92
6	25 grs.	NaCl washed out	N/50	250	.0170	.07
7	25 grs.	H₂O washed	....	250	.0695	.27
8	25 grs.	H₂O washed	N/1000	250	.0740	.29
9	25 grs.	H₂O washed	N/500	250	.0660	.26
10	25 grs.	H₂O washed	N/250	250	.0615	.24
11	25 grs.	H₂O washed	N/100	250	Lost, but almost clear	......
12	25 grs.	H₂O washed	N/50	250	....	......
13	25 grs.	Boiled	....	250	.9060	3.62

The evidence presented in the last two tables supports the view that the NaCl + H₂O soil has suffered some physical alteration which is not readily reversed by the second addition of NaCl. The NaCl added to the soil already diffused by previous treatment with that salt and water is here considered as a physical agent, possessing the power to flocculate clay colloids. To test the reversibility of the chemical reactions occurring when salt solutions are allowed to act upon soils requires a soil treatment involving the application of solutions containing, in appropriate form and quantity, the elements removed by the salt applications. Thus, to restore normal conditions in a soil which has been diffused by a salt-and-water treatment would require the replacement of the absorbed sodium by such metals as were originally present in the soil. The larger amounts of NaCl required to flocculate the colloids of the diffused soil may be due to the increased quantity of colloids present, or to the degree of

diffusion of the colloids, or to a change in the nature of the colloid. However, the fact is patent that more NaCl, or a greater length of time for equal quantities of NaCl, is required to produce effects on the $NaCl + H_2O$ soil commensurate with those on the check H_2O soil. Table III shows clearly the relative effectiveness of varying concentrations of NaCl in flocculating the colloidal matter as measured by the time required for clearing the suspension. Thus N/100 NaCl flocculates the colloidal matter of the washed soil in one hour, while 360 hours were required to accomplish the same result with the $NaCl + H_2O$ soil. Nevertheless, the colloidal matter of the $NaCl + H_2O$ soil seems to be more readily flocculated per unit of NaCl than does that of the H_2O soil, as is shown in Table IV. Thus the $NaCl + H_2O$ soil, when suspended in distilled water, yields a suspension containing 0.8345 grs. of solid matter, while the same soil suspended in N/250 NaCl yields but 0.4570 grs. of solid matter. The deposition of 0.3775 grs. of solid matter, in this case, was brought about by 0.058 grs. of NaCl, or at the rate of 6.5 mgs. of solid matter to 1 mg. of NaCl. Similar calculations for the same suspensions of H_2O soil showed that but 0.14 mgs. of suspended matter was flocculated per mg. of NaCl. Although the NaCl is relatively more effective on the suspended matter of the $NaCl + H_2O$ soil than on that of the control soil, yet, in but one instance, that of the comparatively strong solution of N/50 NaCl, is the influence of the added salt sufficient to flocculate completely the colloidal matter of the $NaCl + H_2O$ soil.

Furthermore, it seemed possible that the transformations manifestly occurring in the physical condition of the soil might also be reflected in some measure in the chemical composition of the variously treated soils and of their colloidal substances. Accordingly these materials were subjected to analysis by the strong hydrochloric-acid digestion method, as recommended by Hilgard for chemical soil studies. However, the results secured up to the present time have not confirmed the above presumption. But to what extent future analytical work will enable us to decipher the relationship of the various factors involved in producing the condition under consideration, is still an open question.

TABLE V

RELATION OF CALCIUM AND MAGNESIUM IN PERCOLATE TO SUBSEQUENT COLLOIDAL DIFFUSION

No.	Soil	Amount of Soil	NaCl	Washed with cc. H_2O	Calcium in Total Washings	Magnesium in Total Washings Lost	Test-Tube Suspensions		Appearance at end of	
							Soil grs.	cc. H_2O	3 days	10 days
1	Anaheim	50 grs.	.00 grs.	1000 cc.	.0058 grs.	.0018 grs.	2 grs.	10	Almost clear	Clear
2	Anaheim	50	.725	1000	.0168	.0018	2	10	Almost Clear	Clear
3	Berkeley	50	.00	1000	.0028	.0017	2	10	Almost clear	Clear
4	Berkeley	50	.725	1000	.0292	.0155	2	10	Very turbid	Very turbid
5	Davis	50	.00	1000	.0032	.0003	2	10	Almost Clear	Clear
6	Davis	50	.725	1000	.0389	.0102	2	10	Very clear	Very turbid
7	Oakley	50	.00	1000	.0046	.0009	2	10	Clear	Clear
8	Oakley	50	.725	1000	.0104	.0027	2	10	Almost Clear	Clear
9	Peat*	25	.00	1000	.0218	.0069	2	10	....	....
10	Peat	25	.725	1000	.0324	.0154	2	10	....	....

* The particular peat soil worked with was so light and fluffy that suspensions could not be made.

CHEMICAL STUDIES OF THE CALCIUM AND MAGNESIUM CONTENT OF THE
PERCOLATE AND THE ABSORPTION OF SODIUM

Our attention was first directed to the possibility of the existence of a relationship between the two factors mentioned in the heading above, by the following experiment, the outline and results of which appear in Table V, page 309.

A review of these data discloses the fact that the application of NaCl to a soil increases the calcium and magnesium found in the percolate as compared with the quantities found in the percolate of the normal soil when leached with distilled water. This is in accord with the results of Kullenberg,[9] Van Bemmelen[10] and the work of others, a good list of which is given by Sullivan.[11] To exemplify the above remarks concerning calcium, let us examine the table with respect to that element. The addition of NaCl to the Anaheim sandy loam and Oakley sandy soil has practically tripled and doubled, respectively, the amount of calcium found in the percolates over that of the percolate from the salt-free soil. In the Berkeley adobe and Davis clay-loam soils the NaCl brings about a much more marked increase of calcium in the leachings. It may be remarked also that the results secured with magnesium are quite parallel to those concerning calcium.

In addition to altering the calcium and magnesium contents of the percolate, the salt treatments materially affected the physical condition of the soil, as shown by a marked retardation of the rate of percolation. All of the soils responded alike to the NaCl treatments, in that they became more impervious and their colloidal matter exhibited a higher degree of diffusion when suspended in water, as shown in the second part of Table V. The degree of imperviousness and diffusion varied, however, with the different soils, and also appeared to be roughly proportional to the increase of calcium and magnesium in the leachings from the soils receiving NaCl. Thus the salt-treated Berkeley and Davis soils, showing notably greater increases in calcium and magnesium in the percolates, were also more highly diffused than

9 Jahrb. Fortsch. Agri. Chem., vol. 8, p. 15, 1865.

10 Landw. Vers. Stat., vol. 21, p. 135, 1878.

11 U. S. Geol. Surv., Bull. 312, 1907.

the other two soils, which were much less affected in both these particulars. Evidently the extent of decomposition of the salt by the soil is a factor in determining the final physical condition thereof, and would certainly seem to indicate that the changes of the physical condition of the soil resulting from salt treatments are considerably more than a mere shifting of the soil particles to new positions, as some investigators would lead us to believe. Moreover, it appears proper to infer that these after-effects of salt treatments can be more properly referred to the salt as a chemical agent than as a physical agent.

If it be true that the chemical reaction between soils and salt solutions results in a chemically equivalent exchange of bases, as Sullivan[12] states, then it seems proper to assume that the calcium and magnesium in the leachings from soils treated as described above represent approximately the amount of absorbed sodium. At least it would appear that the calcium and magnesium in the solutions, less the quantity normally present in distilled-water extractions, is an index of the absorbed sodium. This statement has received further justification in some solubility studies, the data of which have not been published. Undoubtedly considerable quantities of sodium have been removed from the salt solutions by the soil, which in return has given up calcium and magnesium. The absorbed sodium has become so firmly fixed in the soil that no amount of washing can dissolve it; otherwise the wash water after passing through the soil would be slightly alkaline. On the contrary, the first portions of the wash water coming through appear to be slightly acid, which is in accord with the work of Sullivan,[13] Parker,[14] and others, but if the washing is continued the leachings eventually become neutral or just perceptibly alkaline, as is the case when distilled water is in contact with the normal Davis soil. These remarks, supported with stronger evidence from the rapidly accumulating literature on chemical exchanges between salt solutions and soils or silicates, point to the formation, under the conditions herein reported, of a sodium alumino-silicate compound, or possibly a series of such

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[12] *Loc. cit.*, p. 27.

[13] *Loc. cit.*, p. 8.

[14] Journ. Agric. Research, vol. 1, no. 3, p. 1, 1913.

compounds, which resemble most natural silicates in possessing a comparatively inert chemical nature, and which suffer but slight decomposition when in contact with water or are scarcely more than appreciably soluble in water. This hypothesis receives further confirmation in the contention of R. Gans[15] that artificial aluminum silicates behave like natural zeolitic silicates. Moreover, Way[16] clearly recognized the formation of such compounds, and Van Bemmelen[17] is inclined to consider the absorbed salts as fixed in loosely bound chemical combination.

It was originally considered that the substitution of sodium for calcium and magnesium in the soil was a potent factor in bringing about the diffusion of the salt-treated, water-washed soils. However, this first conception attributed the possible effect of the chemical exchange to the double decomposition of the organic salts of calcium and magnesium by the NaCl, which would result in the formation of $CaCl_2$ and $MgCl_2$ and organic compounds of sodium. Since these end-products are all soluble in water, a continuous leaching of the soil with that solvent would be likely to deprive the soil of a portion of its organic matter and of a certain amount of calcium and magnesium. If the organic matter herein referred to can be properly catalogued under those elastic and indefinite terms, humus or humates, then it appears reasonable in the light of Schloesing's work[18] to expect that the physical condition of the soil, depleted of such organic matter, would be seriously affected in the direction already suggested. The loss of such well-known flocculating agents as calcium and magnesium might also be reflected in the changed physical aspect of the soil.

But the cogency of the argument just presented is considerably lessened by the results of the experiment to be described next. Twenty-five gram portions of the Davis soil were subjected to the treatments outlined in Table VI. The soils were then allowed to dry, after which 10 grams of each soil were suspended in 100 cc. of distilled water for 48 hours before the sus-

15 Cited from Exp. Sta. Rec., vol. 31, no. 1, p. 22, 1914.
16 Journ. R. Agric. Soc., vol. 13, p. 123, 1852.
17 *Loc. cit.;* also in Landw. Vers. Stat., vol. 35, p. 121, 1888.
18 Cited from Hilgard, Soils (1911), p. 111.

TABLE VI

The Effect of Removing Humus from the Soil in its Relation to the Diffusion Appearing in the Soil After Salt and Water Treatments

No.	Soil	Treatment	Weight of Suspended Matter from 10 grams in 100 cc. of water
1	25 grs. (Davis soil)	Washed with H_2O	.0184
2	25 grs. (Davis soil)	50 cc. 4N HCl then washed with H_2O	.0118
4	25 grs. (Davis soil)	HCl,* H_2O, NH_4OH, and H_2O	.0250
5	25 grs. (Davis soil)	HCl, H_2O, NaCl, and H_2O	.1216
6	25 grs. (Davis soil)	HCl, H_2O, NH_4OH, H_2O, NaCl, and H_2O	.1842
7	25 grs. (Davis soil)	NH_4OH	.0176

* The symbols used herein designate the soil treatments on the filter paper with the various substances; as indicated, H_2O applications were generally made between applications of the other materials. Solutions approximating normal strength were generally employed.

pension above the deposited material was drawn off. An aliquot of this suspension was evaporated to dryness, gently ignited, and weighed to obtain the data of column 4, in Table VI.

The weight of the suspended matter secured from suspensions of Davis soil which had been subjected to the various treatments gives an index of the extent of the physical effects of such treatments. The treatment with HCl, followed by washing until the filtrate was practically free from chlorides, seemed to reduce the quantity of material capable of being held in suspension, yet the soil had no doubt lost a considerable quantity of its original calcium and magnesium content. This fact certainly indicates that the loss of calcium and magnesium from the soil bears but little relation to the diffusion of the soils as a general proposition.

The soil treatment in the case of No. 4. which simulates the procedure generally employed in humus determinations. with the exception that water is used as a final application, gives a suspension slightly richer in solids than the soil treated with water alone. If, in addition to the treatment just mentioned, NaCl is then added to the humus free soil,[19] the suspension becomes a very turbid liquid rich in solids in a highly diffused state,

[19] The term humus here signifies that portion of the soil's organic matter removed by the treatment in vogue for that purpose.

as shown in the case of No. 6. Evidently the loss of humus and its organic colloids increases, rather than decreases, the amount of material finally found in suspension, for No. 5, receiving HCl and NaCl treatment, yields a suspension containing less colloidal material than does No. 6. In all probability the increase of colloidal material in No. 6 over No. 5 is in no way connected with the loss of organic matter of No. 6, but is more likely to be due to the conditions and treatments involved in extracting the humus. Furthermore, the organic colloids of soils seem to have but little direct relation to the phenomena which appear when certain salts are washed from soils.

That the deflocculated condition of the salt-treated soils might be due in some measure to the loss of calcium and magnesium from the soil, in a manner somewhat analogous to that outlined by Foerster,[20] appeared as a secondary consideration. The actual loss of calcium and magnesium, however, cannot be considered the sole factor in producing the striking conditions observed. For, if that were the case, the application of acids followed with washing should bring about similar results. On this point War-ington has already noted that normal diffusion of the colloids will reappear in a soil which has once been flocculated by acids when the acids and such salts as they have formed are removed by washing. Our experience with soils treated in the manner just described fails to show any marked increase in colloids, as is the case when the soil is treated with NaCl. The treatment with HCl followed by leaching with water seems to retard to a notable extent the rate of percolation through the Davis soil. However, if any new colloids are formed by this treatment, or if the original colloidal content of the soil is thoroughly diffused thereby, as the case may be, then these effects are entirely oblit-erated by the subsequent drying of the soil, for a suspension of the dry soil so treated yields no additional colloidal matter. This fact tends to confirm the view that the loss of calcium and mag-nesium is not alone responsible for the diffusion of the soils.

Furthermore, the writer has shown clearly by a rather simple procedure that a considerable exchange or a direct addition of bases is essential for the production of the diffused condition.

20 Chem. Ind., vol. 28, no. 24, p. 733, 1905.

A solution of N/10 NaCl was allowed to act upon successive portions of Davis soil until practically no more calcium or magnesium was taken up by the solution, so that a solution of chlorides was formed which was quite inert toward this soil. A solution secured in this manner appears to approach the saturation point with respect to calcium and magnesium compounds of the soil. This solution remained practically N/10 with respect to chlorine throughout its successive periods of contact with the soil, and at no time was the solution entirely depleted of its sodium content by the interchange with calcium and magnesium. The application to the Davis soil of a solution secured in the fashion described above and followed by washing with water did not result in such pronounced diffusion as was observed upon the application of N/10 NaCl solution followed by washing with water. It may therefore be inferred that the chemical exchange of bases plays a significant role in the mechanism by which diffusion is produced in soils which have been washed after an addition of NaCl.

By the various lines of reasoning outlined above, the majority of the more obvious possible causes for the extreme diffusion of the soils under discussion have been completely eliminated or at least reduced to factors of little significance. For this reason, more mature thought on the subject has directed our attention to the absorption of sodium, which has been previously mentioned, as the keynote to the deteriorated physical condition of the salt-treated, water-washed soils. The substitution of sodium for the calcium, magnesium, or other bases in the silicate complex, or the direct addition of sodium to such a complex, results, according to our proposed hypothesis, in the formation of new jelly-like colloids, capable of becoming highly diffused when in contact with water. The fact that leaching Na_2CO_3, NaOH, $NaHCO_3$, NaCl, Na_2SO_4, and $NaNO_3$ from the soil brings about the same appearance of the soil and the same physical manifestations of deflocculation, becomes more comprehensible if the view is accepted that the absorption of sodium and the new compounds formed thereby are, in the main, the factors responsible for the deflocculated condition of the soils so treated. Moreover, these various treatments are accompanied by the appearance of widely

different quantities of calcium and magnesium in the percolate, thus affording additional evidence that the increased solubility and the consequent loss of these elements from the treated soils is not the prime factor in causing the ultimate diffusion of the soil colloids. The facts herein presented concerning the absorption of sodium and the formation of new colloidal substances corresponds in the main with the idea of unsaturated silicates and absorption phenomena, as developed by Cameron,[21] Harris,[22] and Loew,[23] and others, in their work dealing with acid soils.

The conception of the causes of the apparent deflocculation, as discussed above, receives tangible substantiation in the results of the following experiment. Twenty grams of Davis soil were subjected to the treatments outlined in Table VII. After washing with water, the soils were dried at room temperature and then 10 grams of each were suspended in 100 cc. of water to secure the figures in the last column. Meanwhile the calcium and magnesium in the total percolates were determined in the usual fashion.

TABLE VII

EFFECTS OF WASHING VARIOUS SODIUM SALTS FROM THE DAVIS SOIL

No.	Soil (Davis) grs.	Treatments	Calcium in Total Percolate grs.	Magnesium in Total Percolate grs.	Weight of Suspended Matter from 10 grams in 100 cc. of water
1	20 grs.	H₂O only	.0017	.0014	.034⁸
2	20 grs.	100 cc N/10 NaOH followed with water	.0015	.0005	.4860
3	20 grs.	100 cc N/10 Na₂ CO₃ followed with water	.0020	.0037	.6500
4	20 grs.	100 cc. N/10 NaCl followed with water	.0108	.0109	.4720
5	20 grs.	100 cc. (approx.) N/10 NaHCO₃ followed with water	.0035	.0086	.4880
10	20 grs.	100 cc. N/10 NaNO₃ followed with water	.0088	.0103	.4340

It is clear that all of the sodium salts used in the above experiment produce approximately the same effects on the colloidal matter of the soil when washed from it, as indicated by the

[21] The Soil Solution (Chemical Publishing Co.), 1911.
[22] Journ. Phys. Chem., vol. 28, no. 4, p. 355; and Michigan Agric. Exper. Sta. Tech. Bull. 19.
[23] Porto Rico Agric. Exper. Sta., Bull. 13, 1913.

amount of material finally found in suspension. All of the salt-and-water treatments yielded suspensions containing more than ten times the suspended matter found in the water-washed soil. From the evidence reported in the above table it seems proper to infer that neither the nature of the added sodium salt, nor the loss of calcium and magnesium from the soil, have much part in the production of the deflocculated condition noted in the salt-treated, water-washed soils. The data of Table VII are also discussed later in their relation to the possible effects of NaOH and the OH-ion on the physical condition of soils.

The interchange of ions between the soil silicates and neutral salt solutions like NaCl or Na_2SO_4, which seems to result in the formation of new colloidal substances, also necessitates the simultaneous presence of free acid or of new salts of the free acid as the calcium or magnesium salts, in the solution bathing the soil particles. As previously discussed, both of these conditions have been encountered in the supernatant liquid of a neutral salt solution in contact with soil and also in the first portion of the percolate coming through a soil to which a neutral salt has been added. The constant presence of the free acid and its soluble salts, together with more or less of the salt originally added, occasions the maintenance of a flocculated condition of the soil colloids, so that any additional colloidal matter which may have been produced is not sufficiently effective on the physical character of the soil to be easily recognized.

If it be assumed that new and additional colloidal material is formed in the soil by virtue of the salt-and-water treatments, then it is most likely in existence prior to the washing process, but its effects on the physical condition of the soil are not manifested until the surrounding medium has become sufficiently dilute, with respect to salts, to allow of a more or less complete diffusion of the soil colloids. The addition of the neutral salts either produces new colloidal matter simultaneously with the chemical interchange of bases, which occurs independently of the washing with water, or in some manner disintegrates the existing colloidal aggregates. The former seems the more plausible, especially in view of certain phases of the work herein presented. In addition we also have evidence that the washing with water alone does not

measureably increase the colloidal content of the soil, nor does it materially affect its physical condition.

At least one interpretation of these facts seems plausible, namely, that the neutral salts or their ions function as the creative agent whereby diffusible colloidal matter is formed, while the washing with water serves in the entirely separate capacity of removing from the sphere of activity any flocculating agents in the shape of soluble salts which may have been present.

Certain modifications of the hypothesis just presented must be considered in order to account for the action on soils of the salts which give an alkaline reaction. First of all, the chemical products that can possibly be formed when the latter class of salts is allowed to act upon soils are on the whole comparatively insoluble and hence possess relatively small flocculating powers. Owing to this fact the washing process, which seems to be essential for the appearance of the diffusion in soils treated with neutral salts, is not such an important factor in case of soils treated with salts giving rise to an alkaline reaction.

Instead of attributing the deflocculation of soils which have received NaOH or alkaline carbonates, wholly to the OH-ion content of the solution or to the alkaline reaction so produced, our present theory, supported by the facts already presented, proposes to account for the diffusion of the soils so treated by the formation of colloidal sodium alumino-silicate complexes under conditions which permit of an immediate deflocculation. Therein lies the difference in the behavior of neutral salts on soils, as compared with that of salts of an alkaline reaction. In all probability somewhat similar compounds are formed in the two cases, but in the first case, with the exception of certain circumstances, the conditions are such as to prevent deflocculation, while in the second case deflocculation is at least permitted and perhaps accentuated.

A Possible Relation Between the Composition of the Soil
    Solution and the Diffusion Phenomena in Certain
        Salt-Treated, Water-Washed Soils

The first two hypotheses formulated to explain the diffused condition of the salt-treated soils dealt largely with the soil itself and with the absorption of sodium by the soil. A third hypothesis

proposes to attribute the diffusion of the soil colloids to changes in the composition of the medium, namely the soil solution. Such a diffused condition of the soil colloids might be brought about by an increase in the OH-ion content of the solution bathing the soil particles. This concept is based on the fact that clay is a negatively charged colloid, and according to the views now held the further addition of negative ions to such a colloidal suspension causes these particles to assume greater charges of like sign, so that they repel each other and thus remain distributed throughout the medium in a stabilized condition. On the other hand, it is held that the introduction of ions bearing an opposite charge to that of the colloidal particles neutralizes the charge associated with the particles, so that they no longer repel each other but gather together in aggregates or floccules. For a more complete discussion and bibliography dealing with these phenomena, the reader is referred to the work of Whitney and Ober.[24] In a more recent review Tolman[25] has advanced a clear conception of colloids and their behavior, which affords us a satisfactory working basis for studies on these substances. According to this author, the surface tension existing between the particles and the surrounding liquid is the factor which determines the degree of dispersion of the particles in the liquid. Thus systems of zero surface tension are at equilibrium. Those possessing a negative surface tension increase, automatically, their degree of dispersion until the zero value is reached, while those of positive surface tension tend to become less dispersed. Since the surface tension referred to is the resultant of many forces, it may be readily affected in numerous ways, as by the mechanical process of grinding, by heating, by the addition of electrolytes, or by the passage of an electric current. Through the application of these considerations we may be able to decipher more clearly and definitely the problems involved in the effects of salts on the physical condition of soils.

It is possible that deflocculants other than the OH-ion may have been introduced into the soil solution by means of the salt-and-water treatments, but the latter factor obviously appears as the most significant deflocculating agent likely to be present

[24] Journ. Amer. Chem. Soc., vol. 23, p. 842, 1901.
[25] Journ. Amer. Chem. Soc., vol. 35, no. 4, 1913.

under the conditions of the experiments and hence merits first attention. Probably the most striking evidence of the possibility that the OH-ions in the soil solution may be justly deemed the cause of the diffusion of the soils with which this paper is chiefly concerned, lies in the well-known deflocculating effect of dilute solutions of NaOH on the soil colloids. Thus the poor tilth and cultivating qualities of lands impregnated with black alkali (Na_2CO_3) has been rather vaguely attributed to the OH-ions derived from the hydrolysis of the Na_2CO_3. This expression fails to offer any explanation of the mechanism whereby the OH-ion induces the observed effects, neither does it allow of any possible effect of the Na-ion on the physical properties of the soil. However, if our interpretations be not too far amiss, there are several reasons, not based on theoretical considerations alone, but substantiated by facts, for suspecting that the OH-ion is of much smaller significance than the accompanying Na or other basic ion in the final effect of the chemical compound on the physical condition of the soil.

The common conception that substances which yield an alkaline reaction on hydrolysis occasion the deflocculation of the soil colloids is frequently accepted without qualification, even by those working with alkali soils, notwithstanding some facts now extant which deny its validity. Thus, as early as 1874 Durham[26] pointed out that clay suspensions cleared more rapidly in strong Na_2CO_3 solutions than in distilled water. Whitney and Straw[27] have also shown that NaOH in dilute solutions tends to stabilize suspensions of colloidal silver, china clay, and lampblack, and that emulsions of turpentine, carvene, and carvol are also acted upon in a similar manner. The behavior of these substances also gave evidence that the maximum stability occurred at certain concentrations of NaOH, above which flocculation was produced and below which the effect of the NaOH was not so pronounced. The investigations of Hall and Morison already referred to substantiate, in the main, the previous citations on the point under discussion. Quite recently Maschhaupt[28] has found that even

26 Chem. News, vol. 30, no. 676, p. 57, 1874.

27 Journ. Amer. Chem. Soc., vol. 29, p. 325, 1907.

28 Landw. Vers. Stat., vol. 83, p. 467, 1914.

0.015 N NaOH has a flocculating effect on the colloidal matter of a sandy loam soil, while more dilute solutions of NaOH stabilized the diffusible colloidal matter. He further asserts that alkali carbonates act much in the same manner. Despite the preceding evidence, Rohland[29] still contends that the flocculation of clay soils by lime is due to the OH-ion.

While working along similar lines, the author has noted that a suspension of the Davis clay loam settles out more rapidly in a 0.05 N solution of NaOH than in distilled water, but that solutions of greater dilution were stabilizing in their effects. On the other hand, no solution of Na_2CO_3[30] proved effective as a stabilizing agent as compared with distilled water, while solutions of Na_2CO_3 stronger than 0.022 N had a decided flocculating effect. This difference in the behavior of NaOH and Na_2CO_3 has not come to the writer's attention before in the literature of the subject, and fails to support the widespread teaching that Na_2CO_3 and salts which hydrolize similarly deflocculate the soil colloids through the agency of the OH-ion. But the most striking feature of the action of NaOH on the soil suspension was the marked resemblance of the soils suspended in that medium to the $NaCl + H_2O$ soil suspended in distilled water. The yield of suspended matter from these two suspensions proved to be of about the same magnitude, as shown in Table II. A cursory consideration of this fact obviously supports the contention that the OH-ion content, or the alkalinity of the suspending solution, may be responsible for the diffusion of the soil colloids in the cases under consideration. However, an interesting point to the contrary lies in the fact that suspensions of the Davis soil in very dilute solutions of NaOH can not be distinguished from suspensions of the same soil in distilled water. That is to say, NaOH solutions of a concentration of N/1500 to N/2000 exercised no recognizable effect on the soil colloids. The concentrations here referred to approach the same order of alkalinity as that found in the solution bathing the particles of the highly diffused $NaCl + H_2O$ soil. Evidently some other factor than the OH-ion

[29] Landw. Jahrb., vol. 44, no. 3, p. 437, 1913; and Landw. Vers. Stat., vol. 85, nos. 1–2, p. 123, 1914.

[30] Baker's analyzed Na_2CO_3 was used in these experiments except where otherwise noted.

content of the solution is either responsible for the diffused con-
dition of the soil colloids, or at least is of material assistance in
producing this effect.

Moreover, it has been demonstrated that the washing out of
the excess NaOH does not materially benefit the injured physical
condition of the soil, although the alkalinity of the soil solution
was thereby reduced to a concentration comparable with that of
the dilute solutions to which reference has just been made.
Actual determinations of the alkalinity of the final portions of
the percolate from soils to which NaOH has been added show
only such alkalinity as the percolate from the normal soil. If
we accept the view brought forth by Cameron,[31] which seems
justifiable, then the percolates from these soils approach, as a
limit, the chemical composition of the soil solution and hence
we may conclude that the alkalinity of the soil solution is of the
same order of magnitude as that of the percolate. The fact that
washing the NaOH from the soil is not accompanied by an im-
provement in the physical condition of the soil may be fairly
interpreted as substantially affirming the view that the OH-ion
is of little moment in the diffusion of the $NaCl + H_2O$ soil, and
possibly has but little connection with the deflocculation of soils
to which NaOH has been added. Furthermore, the facts just
discussed, taken in conjunction with those considered under the
heading of sodium absorption, lend an appearance of reality to
the assumption that the sodium, even in the case of direct addi-
tion of NaOH to soils, is the principal agent in creating the
diffused condition in soils so treated.

Moreover, the writer has found that $NaHCO_3$, Na_2CO_3, and
NaOH have distinctive effects on the soil colloids. In higher
concentrations all three salts prove to be flocculants; in very weak
concentrations, as of the order of N/2000 or less, they seem to
resemble distilled water in their behavior toward the soil col-
loids. In medium concentrations, that is, those less than 0.05
N, NaOH is a deflocculating agent, Na_2CO_3 acts much like dis-
tilled water, while $NaHCO_3$ seems to be a pronounced flocculant.
At least the NaOH and Na_2CO_3 yield a certain amount of
OH-ions, and in the wide range of concentrations employed some

31 Eighth Intern. Cong. Appl. Chem., vol. 15–16, p. 49, 1912.

point must have been encountered at which the OH-ion concentration of these two was the same or approximately so. Yet the two salts exercised a different influence on the soil colloids at all the concentrations used, with the exception of the highest and lowest concentrations. This fact indicates that some other factor than the OH-ion is effective in determining the degree of dispersion of the soil colloids. What application this may have to black alkali lands is a question, for under natural conditions it is most likely that all three compounds, $NaOH$, $NaHCO_3$, and Na_2CO_3, and their respective ions occur.

But the most striking feature of this phase of the problem lies in the fact that the washing out of the soluble matter from separate portions of the Davis soil receiving $NaOH$, Na_2CO_3, and $NaHCO_2$ results in the same way. The soil becomes very impervious and diffuses when shaken with distilled water. Thus the cylinder soils receiving Na_2CO_3 have been exposed to conditions permitting the leaching out of the soluble salts, at least from the surface soil, so that they now exhibit the same peculiarities as the soils treated analogously in the laboratory.

The systems so far considered have been largely made up of soils to which various quantities of $NaOH$, Na_2CO_3 or $NaHCO_3$ have been added. To ascertain to what extent the facts so gained are applicable to the conditions existing in the laboratory samples of $NaCl + H_2O$ soil or to those of the field cylinder soils receiving $NaCl$ and Na_2SO_4, necessitates the measurement of the alkalinity obtaining in these soils. We have attempted to secure some information with regard to the quantity of OH-ions or the alkalinity in the solution containing a suspension of the $NaCl + H_2O$ soil, but the persistent color of this solution has made it impracticable to employ it directly with the various indicators. It would seem, however, from actual titrations made in the usual manner using methyl orange as the indicator, that the alkalinity of the soils in the cylinders receiving $NaCl$ and Na_2SO_4 had been somewhat increased over that of the control soils. But solutions secured from soils treated in the laboratory in a manner similar to the treatment of the field soils failed to verify consistently the above observations. At the present time we are engaged in a study of the reaction of the soil suspensions by the use

of the hydrogen electrode. The results thus far secured indicate that there is not a sufficient quantity of OH-ions in the NaCl — H$_2$O soil to produce the degree of deflocculation observed therein.

If the OH-ion content of the medium is assumed to be the causal agent for the diffusion of the soil colloids, it would appear an equally plausible assumption that the transference of the suspending medium from a diffused soil to the original untreated soil would carry with it the deflocculating agent, so that the second soil would register to some degree the physical manifestations of deflocculation. To test the correctness of this hypothesis the following experiment was undertaken. Twenty-five grams of NaCl + H$_2$O soil were suspended in 250 cc. of water. The colloidal matter of such a suspension normally remains in a stabilized condition for at least three or more weeks, when exposed to laboratory conditions. This suspension was cleared, however, at the expiration of 48 hours by passing it through the Pasteur Chamberland filtering candle under pressure. This was accomplished with considerable care so as to conform to the conditions found by Briggs[32] to yield the most satisfactory results. The solution secured in the manner described from the NaCl + H$_2$O soil was then used as a suspending medium for 10 grams of untreated Davis soil. A comparison of the suspension thus formed with a suspension of the same soil in distilled water disclosed no recognizable difference. Thus it would appear that a transference of the suspending medium of a diffused NaCl + H$_2$O soil to a second untreated soil does not carry with it the agent causing the deflocculation of the first soil. Hence, any hypothesis ascribing the altered physical condition of the NaCl + H$_2$O soil to changes in the soil solution seems untenable.

The value of the results secured by the procedure outlined above may be open to question. To avoid such criticism, the writer made the following experiment, which distinctly shows that the transference of a soluble soil deflocculant from one soil to another by the method employed is susceptible of proof. A N/50 NaOH solution in contact with the Davis soil tends to maintain the soil colloids in a stabilized condition. Such a diffused suspension was subjected to the filtering treatment out-

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32 U. S. Dept. Agr., Bur. of Soils, Bull. 19, p. 31, 1902.

lined above and on passing through the Pasteur filter yielded a clarified solution which had not lost its power to deflocculate the Davis soil. The writer is fully aware that conditions might arise wherein such treatments would considerably modify the deflocculating power of the solute—for example, in case of very dilute solutions where absorption by the soil and filter would be relatively large and possibly of sufficient magnitude to markedly diminish the quantity of deflocculant in the filtrate, which would result undoubtedly in a decrease in the deflocculating power of the solution. A similar reduction in deflocculating power of a solution would also be likely to appear if a solution were subjected to repetitions of the procedure described above.

Despite the evidence above some doubt may still be entertained as to the absence of significant quantities of OH-ions in the films of water on the immediate surfaces of the colloidal particles, especially in view of the probability that the colloidal matter in the diffused soils consists largely of compounds of the chemical nature of sodium silicate, which hydrolizes to some extent in water and eventually gives rise to OH-ions, thereby lowering the surface tension as described by Tolman[33] and likewise producing the conditions obtaining in the "natant" colloids of Hall and Morison.[34] Moreover, the results secured by Briggs[35] on the absorption of alkali hydrates by silica tends to confirm the proposed conception of "natant" colloids. If this be the case, the rate of diffusion of these ions from the films into the more dilute medium would be the factor determining whether it would be possible to transfer a sufficient quantity of these ions, by means of the solution, to be effective on the physical condition of a second, otherwise untreated, soil. Under the conditions of the experiment just cited, a contact period of two days was allowed for such diffusion, which would appear to allow ample time therefor.

Furthermore, as observed by Whitney and Straw[36] and others, the fact that NaOH in certain concentrations tends to stabilize

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[33] *Loc. cit.*

[34] *Loc. cit.*

[35] Journ. Phys. Chem., vol. 9, p. 617, 1905.

[36] *Loc. cit.*

colloidal matter of a comparatively inert chemical nature forms
the basis of an argument which opposes the conceptions herein
presented, and which favors the view that the OH-ion may, after
all, play an important role in the diffusion of colloids. Thus,
systems composed of colloidal silver, lampblack, or relatively
pure organic substances in contact with NaOH probably do not
offer opportunity for the direct addition of the sodium or the
exchange of ions whereby sodium is taken up, a factor which
forms an essential link in the scheme proposed by the writer to
explain the effects of the alkali salts on soils. Also the experi-
ments of Bliss, cited by Whitney and Straw,[37] give an indica-
tion that NaOH may be an effective agent, through the medium
of the OH-ion. No attempt is made, however, to deny the com-
plete ineffectiveness of the OH-ion, for it undoubtedly has an
important influence on the physical condition of colloids, as is
the case with many ions. But with regard to the physical condi-
tion of the salt-treated Davis soil, it is very evident that the
OH-ion is a factor of much less significance than the other ions
associated with it.

The Precipitating Effect of Various Acids and Salts on the Soil Colloids

There seemed some possibility that the presence of some ion
or ions, other than the OH-ion, in the soil solution might be held
accountable for the extreme diffusion of the $NaCl + H_2O$ soil
and soils similarly affected by other salt treatments. Conse-
quently an extensive series of test-tube experiments dealing with
the effects of various acids and salts on the soil suspension were
undertaken. The results of these tests are briefly referred to at
this time in their relation to the condition existing in the salt-
treated, water-washed soils.

It was found that $N/2000$ HCl and H_2SO_4 perceptibly floccu-
lated the soil colloids, as compared with distilled water sus-
pensions of the same soil. To attribute this action wholly to the
H-ion of the acid would, in the writer's opinion, be erroneous,
for no doubt salts are immediately formed when the acid comes

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[37] *Loc. cit.*

into contact with the soil. Nevertheless, it is significant that acids of the low concentration here employed are more efficient flocculants than their salt solutions of similar concentrations. Hence the unneutralized acid in very dilute concentrations undoubtedly exercises a pronounced flocculating power, so that this factor is eliminated as the possible deflocculant in the case of NaCl + H$_2$O soil.

Solutions of the chlorides, sulphates, and bicarbonates of calcium, sodium, ammonium, and potassium, were also studied with regard to their effects on the colloidal matter of soils. These salts in solutions ranging in concentration from N/1500 to N/500 possessed distinct flocculating powers. Solutions of higher concentrations were likewise flocculating in their effect, while more dilute solutions behaved similarly to distilled water. Hence the diffused condition of the NaCl + H$_2$O soil cannot be attributed to the mere dilution of the neutral sodium salts or of the simple salts formed by reactions between the added salts and the soil silicates. As previously indicated, this statement must not be construed to include the systems soil + NaOH, or soil + Na$_2$CO$_3$, but must be considerably modified to express the facts existing in those cases.

The Effects of Washing Various Salts from the Soil with Water

The washing out of KCl and NH$_4$Cl from the Davis soil with water gave essentially the same results as accompanied the removal of the sodium salts by the same means. On the other hand, the leaching out of calcium salts seemed to leave the soil colloids in a more flocculated condition than in the normal, untreated soil, though this effect was by no means so pronounced as when the calcium salts were allowed to remain in contact with the soil particles. According to the ideas herein presented, the effect of a salt solution, either while in contact with the solid particles or after its removal from the soil by washing with distilled water, upon the physical condition of soils or complex silicates of such a character as to admit of chemical exchange of ions, is, in a measure, dependent upon the nature of the chemical

bodies formed by virtue of this interchange of ions.[*] The soluble products, including the salts of calcium, magnesium or other bases, which are formed when salt solutions are allowed to act upon soils, must be considered, if a true conception of the physical effects of the added salts is to be secured. In addition, the individual properties of the new silicate complex, which is formed simultaneously with the exchange of ions, must be recognized as bearing significantly on the final effects of the added salt on the physical condition of the soil. Undoubtedly, these factors have a bearing on the effects of salts on the capillary movement of water in soils, and make impossible the direct application of physical laws concerning surface tension and densities to the phenomena of capillary rise, as Briggs and Lapham[38] have attempted. Instead, the factors discussed above may help to harmonize the observations made by these investigators with the more recent findings of Kossovich.[39]

The addition to soils of KCl, NH_4Cl, $NaNO_3$, Na_2SO_4 or NaCl, and in fact most neutral salts, has been shown by Way,[40] Eichhorn,[41] Henneberg and Stohman,[42] Peters,[43] Van Bemmelen,[44] Bradley,[45] Curry and Smith,[46] and others, to result in increasing the quantity of calcium, magnesium and other metallic ions in the solution secured from soils so treated, as compared with the same soils receiving distilled water. Furthermore it has been shown by Hall and Morison,[47] Davis,[48] Patten and Gallagher,[49] Masoni,[50] and others that calcium and magnesium salts possess more pronounced flocculating powers than the corresponding salts of the alkali metals. This fact may account for the different rates at

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[38] U. S. Dept. Agric., Bur. of Soils, Bull. 19, 1902.

[39] Cited from Exp. Sta. Rec., vol. 25, no. 9, p. 824.

[40] *Loc. cit.*

[41] Cited from Sullivan, *loc. cit.*, p. 12.

[42] Cited from Sullivan, *loc. cit.*, p. 13.

[43] Landw. Vers. Stat., vol. 2, p. 113, 1860.

[44] *Loc. cit.*

[45] Oregon Agric. Exper. Sta., Bull. 112, 1912.

[46] New Hampshire Agric. Exper. Sta., Bull. 170, 1914.

[47] *Loc. cit.*

[48] U. S. Dept. Agric., Bur. of Soils, Bull. 82.

[49] U. S. Dept. Agric., Bur. of Soils, Bull. 52, 1908.

[50] Abstract in Journ. Chem. Soc. London, vol. 102, no. 597, p. 677, 1912.

which the same strength of different salt solutions operates to clarify suspensions from different soils. Moreover, the addition of these salts seems to bring about a decided increase in the colloidal content of the soil, which is obviously manifested when the soluble salts are removed by distilled water. On the other hand, the introduction of calcium salts to a soil does not apparently bring about the production of a colloidal complex, although some interchange of ions occurs. In fact, the addition of $CaCl_2$ followed with washing seems to have the opposite effect on the Davis clay-loam soil. For these reasons it seems evident that the insoluble as well as the soluble products formed by the interaction of salts on soils must be considered as important factors in such practices as prescribe the use of soluble salts on soils.

It is apparent that at least the Na, K and NH_4 ions form a colloidal substance upon their introduction into the silicate complexes of the Davis soil. The Ca-ion, and probably others, form, on the contrary, non-colloidal substances when introduced into the complex silicates of the Davis soil. It is also made clear that the acid ion is of little importance in the phenomena following the washing out of salts from the soil, by the fact that $NaNO_3$, NaCl and Na_2SO_4 all operate to produce approximately the same results.

Some General Observations on Other Peculiar Appearances Accompanying the Washing Out of Certain Salts from Soils

Stewart[51] in a recent paper attributes the color of the nitre spots to the action of sodium or potassium nitrates on the organic matter of the soil. Bearing somewhat upon this subject, we have noted that the addition of NaCl or Na_2SO_4 to a soil materially increases the organic matter in the supernatant solution if the depth of color of such a solution can be relied upon as an index of the quantity of organic matter contained therein. But the most striking results in this connection appear when these neutral salts are removed from the soil by washing. The soil itself assumes the typical gray color of alkali soils in the field, and the

[51] Journ. Amer. Soc. Agron., vol. 6, no. 6, p. 247, 1914.

filtrate takes on a rich, dark brown color, not unlike the usual NH_4OH humus extract. Frequently the soil when dry is covered with a thin layer of hard, black, organic matter. Indeed the resemblance between the $NaCl + H_2O$ soil, the water in contact with it, or its percolate, and the natural alkali soils and the water bathing their particles, is so striking as to deceive even those experienced in the handling of ''black alkali'' soils.

The increased solubility of the organic matter in the salt-treated, water-washed soils, as indicated by the increased depth of the brown color, cannot be due to the presence of the NaCl as a chemical entity, for the color does not appear until after some of the salt has been removed from the soil by washing. There can be no doubt that the $NaNO_3$ by means of an interchange of ions with the organic salts of calcium or magnesium does affect a greater solubility of organic matter, but this solubility may be greatly increased if the added salt is washed from the soil. This fact may be of assistance in accounting for the color of the nitre spots.

In agreement with Van Bemmelen[52] and Warington,[53] we have also noted the appearance of fluffy, flocculent colloids passing through the filter paper, when the added salt is practically washed from the soil. These colloids coagulate when in contact with the filtrate containing the soluble salts from the soil.

One other point which has not received prior attention, but which seems of sufficient importance to be mentioned at this time, is the fact that all of the salt need not be washed from the soil to produce the effects noted. In another series of experiments, which will be reported in detail later, 3200 cc. of a 1.5 per cent solution of NaCl (which was intended to represent the strength of the soil solution when 0.3 per cent of NaCl is added to the soil under optimum water conditions) was passed through 1600 grams of Davis soil. The soil was affected to a greater extent than a soil receiving a similar quantity of NaCl, namely 4.8 grams, or than a third soil receiving a similar quantity of NaCl, which in addition was leached with 3200 cc. of water. The injury to the first soil was greater than to the other soils despite the fact that

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[52] *Loc. cit.*

[53] *Loc. cit.*

a small quantity of salt remained in contact with the soil. These observations lend further confirmation to the fact previously observed, that a second addition of NaCl to a NaCl + H₂O soil does not cause the reversion of the soil to its original condition.

GENERAL DISCUSSION OF THE EFFECTS NOTED AND THEIR APPLICATION TO SOIL STUDIES AND THE MANAGEMENT OF SOILS

In the discussion on the possible relation of the calcium and magnesium content of the percolate to the diffused condition of salt-treated, water-washed soils, attention has already been called to the fact that the phenomena, first observed in case of the cylinders containing Davis soil, also appeared in three other soils of widely different types. Evidently the effects observed when added salts are washed from soils by distilled water, are not peculiar to any particular type of soil, but are more or less general in their application. Some soils, as those which do not offer replaceable calcium or magnesium to exchange for sodium or other ions of salt solutions, would probably react to a much less extent than those soils which do react with salt solutions. The degree to which the soil is affected by the salt-and-water treatments is apparently dependent upon the amount of exchange of bases, or the direct addition of bases which occurs. This, of course, varies markedly with different soil types and is probably closely associated with complex silicates of which mention has already been made. This conception conforms, in the main, with the ideas brought out by Knop,[54] Van Bemmelen,[55] and Warington,[56] with respect to the absorption of salts by soils. Moreover, Kossovich[57] has noted that NaCl exercises a more pronounced effect on capillary rise in clay soils than in sandy soils.

There can be but little doubt that the effects of salts on the physical and chemical properties of soils has a wide range of application to alkali soils and their management. Moreover, the

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[54] Cited from U. S. Dept. Agric., Bur. of Soils, Bull. 52, p. 19.
[55] *Loc. cit.*
[56] *Loc. cit.*
[57] *Loc. cit.*

peculiar phase of these effects under consideration would seem to have particular significance in that connection. First of all, these soils contain, as a general rule, sufficiently large quantities of salts to be commensurate with those used in the experiments reported above. Secondly, the natural rainfall, irrigation practices, and drainage operations often wash the salts out of the top layers of soil, so that this soil would be exposed to the conditions likely to produce the inferior physical qualities attendant upon deflocculation.

During the late winter and early spring months the writer had occasion to observe the standing water in the depressions of the alkali lands near Fresno, California. To all appearances the underdrainage of these low areas would be practically impossible, owing to the imperviousness of the soil, which upon examination reveals all the characteristics of the diffused salt-treated, water-washed soils. Besides, the gray appearance of the soil when dry, and the striking resemblance of the supernatant liquid to that above the soils in the cylinders, would certainly lead one to believe that even under natural conditions the washing out from and the dilution of the salts in alkali soils has much in common with the artificial production of similar conditions. Heretofore, the depressions and the remarkable imperviousness of their soils have been attributed to the presence of Na_2CO_3.

It would seem that the deflocculation effects exhibited by soils when added salts are washed from them would have particular bearing upon the reclamation of alkali soils by underdrainage. Yet the possible application of this feature to alkali reclamation seems to have been omitted from the literature dealing with this subject.[58] Cameron and Patten[59] observed somewhat similar lowering of the rate of percolation, followed, however, by an increase later as the washing out of the salts progressed. Hare,[60] in a recent paper describing tank experiments dealing with the effects of alkali salts on soils and crops, does not note any possible effect of the added salts on percolation through the soils receiving them, but does comment on the observation that Na_2SO_4

[58] Hilgard, Soils, 1911, chap. 22, and U. S. Dept. Agric., Bur. of Soils, Bull. 35, 1906.

[59] Journ. Amer. Chem. Soc., vol. 28, p. 1639, 1906.

[60] New Mexico Agric. Exper. Sta., Bull. 88, 1913.

was more difficult to leach from the soil than Na_2CO_3 or $NaCl$. Specific information on the physical condition of the drained alkali soils of the various drainage experiments is lacking. Even the recorded observations of a general nature are indefinite and discordant. Thus at Salt Lake,[61] Tempe,[62] and North Yakima,[63] the effect of drainage has not appeared to have benefitted the physical condition of the soil, while at Fresno,[64], Billings,[65] and elsewhere, the drained soil appeared to be superior with respect to physical condition than the undrained soil. Owing to the inadequacy of these reports in that no definite measurements of alteration in the physical condition of the soil are given, they cannot be accepted as a final expression of the effects of drainage of alkali soils.

The behavior of the Davis soil in the cylinders and the general trend of the laboratory experiments seem to the writer convincing arguments that the drainage of these cylinder soils in their present condition would be practically, perhaps absolutely, impossible. Underdrainage, supplemented with powerful flocculating agents, might serve as a feasible plan whereby the excess salt could be removed from such soils.

That natural alkali soils are not strictly comparable with the cylinder soils to which single salts have been added is patent, and this may account, in a measure, for the general discrepancy between the behavior of certain natural alkali soils and that of alkali soils made artificially by the addition of salts. The washing out of salt mixtures, as in the case of natural alkali soils, may have an entirely different effect than the washing out of a single salt. It has, however, been shown in this laboratory that the washing out of certain mixtures of salts from the Davis soil has resulted in the same way as washing out single sodium salts. On the other hand, the time for the reaction of the salt in the soil

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[61] Dorsey, C. W., U. S. Dept. Agric., Bur. of Soils, Bull. 43, p. 16, 1907, and Bull. 35, p. 181, 1907.

[62] Dorsey, C. W., U. S. Dept. Agric., Bur. of Soils, Bull. 35, p. 190, 1907.

[63] *Loc. cit.*, p. 189.

[64] Mackie, W. W., U. S. Dept. Agric., Bur. of Soils, Bull. 42, p. 43, 1907.

[65] Dorsey, C. W., U. S. Dept. Agric., Bur. of Soils, Bull. 44, p. 18, 1902.

being comparatively unlimited in case of the natural soils, it may considerably alter the end-points and end-products and thus introduce a new factor. The constant up-and-down movement of the soluble salts in the soil, the alternate drying and wetting of the soil, and the effects of thermal changes on the soil, may partially obliterate the true effects of washing certain salts from soils. In addition, the relation of calcium, magnesium and other bases to the sodium may be modified by the conditions just mentioned, so that different equilibria are established. Furthermore, the nature of the soil, especially with respect to the original content of colloidal substances and hydrated silicate complexes, must be taken into account. Thus the effect of draining salts from sandy soils free of colloids may be so small as to pass unrecognized, while similar drainage from heavier types of soils would produce marked effects. The colloidal content, too, and the state of diffusion thereof, in our drained alkali lands, may be a direct result of the first natural introduction of the salts into and their subsequent removal from the original soil, the exact physical condition of which may be only surmised. Hence we have no means for securing evidence as to the exact salt effects under natural conditions.

As suggested by Mayer,[66] the physical effects resulting from washing sea salts from the soil may be as injurious to the growth of plants as the direct toxicity of the salt itself. Our experience with the cylinders serves to confirm this idea, for despite the fact that the top foot of soil is almost free from salts, it seems impossible to secure a satisfactory growth of plants. A pot experiment, to be reported upon later, also gives substantial proof that the deflocculated soil, comparatively free from salt, offers a far less congenial home for barley plants, at least during the early stages of growth, than the same soil containing as high as 0.3 per cent of NaCl.

The inability of the plants to make a satisfactory growth in the highly deflocculated soils appears, from a cursory consideration of the conditions, to be due to the lack of available moisture. Although the deflocculated soils may seem to be moist, yet the quantity of water which the plants have at their disposal is

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66 *Loc. cit.*

probably insufficient to promote normal growth. At least this condition is suggested by the moisture equivalents of the defloc-culated $NaCl + H_2O$ soil as determined with the centrifugal machine developed by Briggs. In addition to the low availability of the moisture in such soils as an inhibiting factor, the rate of movement of water through such soils must also be considered in its relation to the growth of plants. From all appearances, it seems justifiable to predict that the movement of water through the highly diffused soils is so slow as to fail to resupply the area occupied by the roots from the more moist soil layers lying adjacent to the root area.

The observed effects of washing salts from soils may also have some bearing upon fertilizer practices and the results on crop plants secured therefrom. The salts used as fertilizers undoubt-edly effect certain modifications of the physical condition of soils. It is also true that the washing out from the soil of at least some of these salts brings a far greater change in the physical properties of the soil than that accompanying the ap-plication of the salts. Probably no instance with respect to this feature, as a phase of soil management, is so patent as that con-cerning the use of $NaNO_3$. Hall[67] comments upon the inadvis-ability of applying this material under certain conditions be-cause of the deflocculating effect of the alkalinity due to residual sodium carbonate. Warington[68] also notes the deflocculating effect of $NaNO_3$ and refers to it as being particularly noticeable after heavy rains. More recently McGeorge[69] has observed a marked retardation of percolation through Hawaiian soils receiv-ing applications of $NaNO_3$, but attributes this effect to some reaction between the added salt and the organic matter of the soil. Undoubtedly the application of $NaNO_3$ to soils under cer-tain circumstances has resulted in a deterioration of the physical condition of the soil, although the $NaNO_3$, as a salt, is in itself a flocculating agent.

The writer has produced marked deflocculation in the Davis soil by applying $NaNO_3$ and subsequently washing the soluble

[67] The Soil, p. 252, 1910.

[68] *Loc. cit.*

[69] Hawaiian Agric. Exper. Sta, Bull. 35, 1914.

salts from the soil with water. The use of the NO_3 radical by plants or bacteria, thereby leaving the sodium, could not have occurred to any extent in this case, for the whole process required no longer than two hours, and was carried out in a filter. The filtrate at no period in the washing process showed sufficient alkalinity to account for the deflocculation. Hence the former conception that residual Na_2CO_3 causes the deflocculation seems untenable, and some such hypothesis as has been advanced in this paper must be adopted to explain the unfavorable physical condition frequently existing in soils receiving applications of $NaNO_3$.

With respect to fertilizer salts in general, Hall[70] calls attention to the deflocculation following the use of neutral salts on soils, but believes the effect is due to alkalinity arising from the absorbed base. Hessler[71] has noted the increase in coherence of the soil particles when $NaCl$, $NaNO_3$ and kainite have been applied to soils. Hoffman,[72] however, could not detect any difference in the interior surface of soils due to fertilizer applications of the usual magnitude. It is of interest to note that no attempt is made to correlate the inferior physical condition of salt-treated soils with the process of leaching the salts from them.

However, potassium and ammonium salts are effective in the same direction as sodium salts when washed from the soil, although they are generally considered flocculating agents when in contact with certain colloidal particles. Hence, to be fully comprehensive and expressive of the whole truth, studies on fertilizer effects should involve not only the conditions under which the salt or salts are present, but also those conditions which not infrequently arise in nature, whereby the soluble salts are removed from the soil by processes analogous to washing the soil with water.

The nature of the clay colloids and the cause of the relatively high degree of deflocculation which they assume when suspended in water have long been subjects of much conjecture and much

70 *Loc. cit.*

71 Cited from Exper. Sta. Rec., vol. 31, no. 2, p. 123, 1914.

72 Landw. Vers. Stat., vol. 85, nos. 1–2, p. 123, 1914.

debate. Hilgard[73] has consistently maintained that the power of such colloids to remain in a stabilized condition is not to be attributed solely to the fineness of division of such particles, but that other factors may be responsible for that condition. In agreement therewith, our experience, which has been presented in this communication, has led us to believe that the chemical nature of the body itself and that of the medium, determine in a large measure the condition in which the colloid may exist.

The extent to which the factor considered in this paper may be applicable to agricultural practice can be better surmised than asserted at the present writing, but it seems highly possible that the modifications of the physical condition of the soil, due to washing out the soluble salts, under circumstances involving fertilizer applications or natural alkali soils, will be reflected in the inferior tilling qualities of the soil, in the increased resistance offered by such soils to root penetration, in the lack of air space and air movements, in the deflocculated soil, and in the moisture and temperature relations of such diffused soils. The movement of moisture in soils by surface tension and osmotic pressure or under gravitational attraction, appears to be particularly dependent upon the degree of deflocculation of the soil colloids.

Besides affecting the physical condition of the soil, the leaching out of soluble neutral salts from soils is, as has been previously shown, frequently accompanied by notable quantities of calcium and magnesium in the percolate. Thereby the soil sustains a considerable loss of calcium and magnesium, which may in the course of time be of sufficient magnitude actually to deplete the available supply of these plant-food elements in the soil. The bacterial flora and bacterial activity of soils subjected to the treatments outlined above are liable to be considerably modified and to all appearances in a harmful direction. Thus all the factors of soil fertility are likely to be measureably affected through the process of washing salts from soils; consequently the crop-producing power of the salt-treated, water-washed soil is apt to be considerably modified.

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[73] Soils, chap. VI.

SUMMARY

1. The Davis clay-loam soil to which surface applications of solutions of NaCl, Na₂SO₄ and Na₂CO₃ had been made became very impervious to water, difficult to cultivate, and manifested the characteristics of a high degree of diffusion, although these salts have been shown to exercise flocculating powers on suspensions of this soil.

2. The salt-treated soils referred to were in cylinders exposed to natural conditions.

3. Examination of the soils showed that the salts had moved downward into the lower layers of soil and that only the surface soil had been affected in the direction described.

4. The deflocculated condition resulting from adding certain salts to and subsequently washing them from soils can be reproduced in the laboratory.

5. The deflocculation of soils treated in the manner described above is intimately associated with the leaching of the NaCl and Na₂SO₄ down into the lower layers of soil by water. In the case of Na₂CO₃ the leaching process is not so essential for the diffusion of the soil colloids.

6. The addition of NaCl, Na₂SO₄ and Na₂CO₃ to the Davis soil when followed with applications of water was particularly effective in diminishing the rate of percolation through the soil so treated.

7. NaCl and Na₂SO₄ in constant contact with the Davis soil increased the rate of percolation, except when a comparatively dilute solution of NaCl was slowly passed through the soil for a considerable period of time.

8. The Davis soil treated with NaCl, NaOH, Na₂CO₃ and other salts, followed by leaching with water, yields a suspension in water containing approximately ten times as much solid matter as the same soil washed with water only. A real diffusion in such salt-treated soils seems evident.

9. The soil once diffused by washing out added NaCl requires considerably more salt to completely flocculate it, than does the water-washed soil. Likewise the injured physical condition of such soils is not readily repaired by a second addition of NaCl.

10. The portion of the organic matter of the soil known as humus has little or no connection with the appearance of diffusion in salt-treated, water-washed soils.

11. The diffusion in soils treated as described above seems to be closely associated with the direct addition of sodium to, or with the absorption of sodium by the soil, thereby producing a new silicate complex of a colloidal character in the soil.

12. This silicate complex is formed simultaneously with the interchange of ions occurring between the salt and the soil.

13. The washing process serves, in the case of neutral salts, to remove flocculating agents.

14. The loss of calcium and magnesium from the soil bears little or no relation to the flocculation appearing in salt-treated, water-washed soils except in so far as it may be a measure of the absorbed sodium.

15. The presence of the OH-ion does not seem to be an essential factor in the diffusion of salt-treated, water-washed soils.

16. Na_2CO_3 and $NaOH$ produce markedly different effects on suspensions of the Davis soil.

17. The acid ion of the salt is not an important factor in the deflocculation phenomena following the washing out of salts from soils.

18. Sodium, potassium, and ammonium seem to produce the colloidal silicate complex when salts of these metals are applied to soils, while calcium does not.

19. Dilute solutions of acids and salts possess flocculating powers on suspensions of the Davis soil.

20. It is not essential in every case to wash all of the salt out in order to bring about diffusion.

21. The facts presented are discussed in their relation to the reclamation and management of alkali lands, and in their application to the use of soluble salts as fertilizers.

INFLUENCE OF THE COMPOSITION AND CONCENTRATION OF THE NUTRIENT SOLUTION ON PLANTS GROWN IN SAND CULTURES

BY

ARTHUR HUGO AYRES

INTRODUCTION

Since the recognition of the fact that the mineral content of the plant body is derived from the mineral constituents of the soil, the part which the soil solution takes in the nutrition of the plant has been the subject of numerous investigations by chemists, plant physiologists, and soil scientists, who have made large contributions to our knowledge in this important field. The early investigations of Knop and other plant physiologists showed conclusively that the elements which are essential to plant growth are carbon, hydrogen, oxygen, nitrogen, sulphur, phosphorus, potassium, magnesium, calcium, and iron. As most of this work was done before the development of the new chemical and physical theories, in regard to solutions in particular, the problems dealing with the absorption of these elements remain for explanation in the light of this new knowledge. The modern period of research in this field has thus been characterized by an intensive study of the absorption of nutrient elements by the plant. The earlier conceptions, which had a marked tendency to link each element with some specific physiological process or with the development of some morphological part of the plant, have been

largely discarded in view of the recent investigations, which have shown that plant growth is not a simple function of any any particular element, but is to a very large extent influenced by the combinations of elements in the solution from which the plant derives its nourishment. Thus while calcium may in certain cases act as a neutralizer of oxalic acid,[1] it exhibits a more general function of antagonism for salts of potassium, sodium, magnesium, and other salts which would be toxic if calcium were not present.[2] While this antagonistic function may be characteristic, it would seem from the experiments of Tottingham[3] that either this antagonistic action of calcium or the toxic effects of magnesium are influenced by the total concentration of the solution. Tottingham, therefore, concludes that the injurious effects of magnesium depend not only on the amount of calcium present but also upon the complex balance between all the salts in the solution. It follows that while the later investigations have undoubtedly given a wider conception of the rôle of the various nutrient elements, the exact relation which exists between the recognized nutrient function of these elements and the balancing function in the solution is not definitely known.

The part which the total concentration of the solution takes in the complicated problem of plant nutrition is by no means clear. On the one hand, the experimental evidence of Cameron[4] and his co-workers shows that the plant growing in water culture is not influenced to any extent by wide variations in the total concentration of the solution, a view which is further supported by the researches of Tottingham,[5] who concludes that nutrient solutions ranging from 0.01 per cent to 0.14 per cent do not affect the dry weight in the case of wheat grown in these solutions. A similar view is taken by Stiles,[6] who thinks that the individual variation of plants grown in water cultures is as large or larger than that which is often accredited to a variation in the compo-

[1] Schimper, Flora, vol. 73, pp. 207–261, 1890.

[2] Loew, Flora, vol. 75, pp. 368–394, 1892; and U. S. Dept. Agric. Bur. Plant Ind. Bull. 45, 1903; Osterhout, Bot. Gaz., vol. 42, pp. 127–134, 1906. and vol. 44, pp. 259–272, 1907.

[3] Tottingham, Physiol. Res., vol. 1, pp. 133–245, 1914.

[4] Cameron, Jour. Phys. Chem., vol. 14, p. 320, 1910.

[5] *Loc. cit.*

[6] Stiles, Ann. Bot., vol. 29, pp. 89–96, 1915.

sition of the solution. In decided contrast to the evidence cited above, we have the investigations of Hall, Brenchley, and Underwood,[7] who conclude, on the basis of their results with barley plants grown in a standard solution of four different concentrations, that "the growth made by plants in the soil solution is in the main determined by the amount of plant food they contain," and that "the concentration of the nutrient solution within certain wide limits, irrespective of the total amount of the plant food available, is a factor in the rate of plant growth which varies directly though not proportionally with the strength of the solution in the particular nutrient or nutrients limiting the growth." The experiments of Shive[8] are of considerable interest in this connection. Wheat was grown in solutions of three different total concentrations, 0.1, 1.75, and 4.00 atmospheres, in terms of possible osmotic pressure. The solution used was the three-salt solution first used by Birner and Lucanus[9] containing $Ca(NO_3)_2$, $MgSO_4$, and KH_2PO_4. All possible sets of proportion of these salts were included for increments of change equal to one-tenth of the total possible osmotic pressure. As judged from the extensive quantitative data collected, Shive concludes that the growth of wheat plants in solutions of any given salt proportion is determined by the concentration of the medium.

In the course of some experimental work concerning the dropping of flowers by F_1 species-hybrids of *Nicotiana*[10] it seemed desirable to grow a considerable number of plants in sand cultures which would vary widely both as to the principal nutrient elements, nitrogen, phosphorus, and potassium, and as to the total concentration of all of the nutrient salts. The marked influence of the nutrient factors upon the growth of the plant has afforded an excellent opportunity for a somewhat detailed study of the influence of the composition and concentration of the nutrient solution upon the growth of one of the higher seed-plants of herbaceous character.

[7] Hall, Brenchley, Underwood, Jour. Agric. Sci., vol. 6, pp. 278–301, 1914.

[8] Shive, Physiol. Res., vol. 1, pp. 327–396, 1915.

[9] Birner and Lucanus, Landw. Versuchsstat., vol. 8, pp. 128–177, 1886.

[10] Goodspeed and Ayres, Univ. Calif. Publ. Bot., vol. 5, no. 9, 1916.

The Use of Sand as a Culture Medium

The ease with which solutions can be prepared and subsequently analyzed has made the water-culture method especially desirable in investigations of the rôle of nutrient substances in plant growth. A solution has generally been recognized, however, to be otherwise undesirable as a medium for the growth of the higher plants, since the root system is kept, during the course of the experiment, in an unnatural environment. Thus, while this method serves admirably for analytical purposes, it seems probable that the plant thus subjected to an unnatural environment will suffer certain more or less serious physiological disturbances. In this connection, it is a well-established fact that the development of root hairs is much greater in sand than in water,[11] the resistance of the substratum favoring root-hair production.[12] Roots in general grow longer and thinner in water than in sand or moist soil. Hall, Brenchley, and Underwood[13] think that the more vigorous growth of barley in sand, as compared with water cultures, is due to more efficient aeration of the former. It would seem, therefore, that sand is preferable to water as a culture medium, since in sand cultures the physical conditions present about the root system more nearly simulate those found in the soil. It is still a question just what part these physical conditions may have in plant nutrition. Undoubtedly such physical reactions as capillarity[14] and adsorption[15] must be important factors, since both the absorption and availability of nutrient salts would be affected by these physical phenomena. Breazeale[16] has shown that the effect of concentration in sand cultures is very different from that in water cultures, the best concentration for wheat in water being three hundred parts per million, while in sand it is in the vicinity of two thousand five hundred parts per million, an effect which is no doubt largely due to the adsorption of certain salts or ions by the sand particles.

[11] Schwarz, Bot. Inst. Tübingen, vol. 1, pp. 135–188, 1883.
[12] Snow, Bot. Gaz., vol. 40, pp. 12–43, 1905.
[13] *Loc. cit.*
[14] Bell and Cameron, Jour. Phys. Chem., vol. 10, p. 659, 1906.
[15] Schreiner and Failyer, U. S. Dept. Agric. Bull. 32, 1906.
[16] Breazeale, Science, n. s., vol. 22, pp. 146–149, 1905.

The physical effects of sand as a medium for plant growth have been shown recently in a striking manner by McCall,[17] who added to sand the solutions which Shive[18] used as water cultures, with the result that much larger quantities of the nutrient salts were required than when the same species of plant was grown in water culture. The sand-culture method was selected for the present work with the above evidence in mind, and also because the growing period of the tobacco plant is long and this method precluded the tedious changing of solutions necessary when the water-culture method was used.

EXPERIMENTAL MATERIAL

The plant which was used in the present series of investigations was a tobacco of hybrid origin derived from a cross between *Nicotiana sylvestris* (U. C. B. G. 69/09) and *Nicotiana tabacum* var. *macrophylla* (U. C. B. G. 22/07) and known in the University of California Botanical Garden as U. C. B. G. H38.[19] The plants to be used were raised from seed and were transferred as seedlings to the sand from the flats in which they were grown after carefully washing the roots free from adhering soil particles. In picking out seedlings from the flats care was taken to choose from the large number of plants available only those which were most nearly uniform with reference to size and general appearance. The plants were kept during the experiment in a well-ventilated greenhouse.

The sand used was a light-colored beach sand which on analysis by means of the acid-digestion method of Hilgard showed the following composition:

Fe_2O_3	0.592 per cent	P_2O_5	0.004 per cent
Al_2O_3	0.46 per cent	MgO	0.28 per cent
K_2O	Trace	CaO	0.06 per cent

The water-holding capacity was 22 per cent when saturated. The sand was prepared for the experiment by washing in a heavy stream of tap water which was allowed to percolate through

[17] Unpublished work.

[18] *Loc. cit.*

[19] Setchell, Univ. Calif. Publ. Bot., vol. 5, pp. 1–86, 1912.

a column of the sand for a period of twenty-four hours. The excess of tap water retained by the sand was in turn washed out with distilled water. While this sand is inferior to the best grade of pure quartz sand in freedom from inorganic material, it is unable to supply available nutrient elements in sufficient quantity to cause any perceptible increase in growth (pl. 14). Two thousand gram portions of the sand treated as above were weighed into six-inch flower-pots which had been previously prepared by dipping them into melted paraffin. The paraffining effectually closed the pores and prevented the absorption of the culture solution by the pot.

DISTRIBUTION OF NUTRIENT SALTS

The pots were divided into three different groups designated as series I, II, and III, each series consisting of twenty pots divided into groups of five pots each, and a duplicate in each case, making forty pots in all in each series. In series I, nitrogen, as $NaNO_3$, was the varying factor within each group, the weight of each of the other salts being held constant. Thus, in series I, the pots 1 to 5 in each of the four groups contained $NaNO_3$ as follows: 0.02, 0.2, 1.0, 2.0, 3.0 grams. In a similar manner phosphorus and calcium, as $Ca(H_2PO_4)_2$, were varying factors in series II, while in series III potassium, as K_2SO_4, was varied. As noted above, the twenty plants of each series were divided into four groups designated respectively as A, B, C, and D, each group consisting of five plants and a control for each. The weight of one varying factor remained the same in pots of like number through all four groups. Thus plants I A 1, I B 1, I C 1, and I D 1 each contained 0.02 grams of $NaNO_3$, and I A 2, I B 2, I C 2, and I D 2 contained 0.2 grams of $NaNO_3$. But from group A to D the weight of the other nutrient factors decreases, so that group D contains two-thirds, C one-half, and D one-fourth the weight of each of these nutrient factors as present in the A group. The effect of this distribution of salts is to give at least three important variables. First, the single nurient salt in increasing proportions from plant 1 to plant 5 in each group, and second, the factor of total concentration which decreases from group A

to group D in each series. The third important variant, the balance of salts in the solution, follows as a matter of necessity, since the single nutrient salt added in increasing quantities from plant 1 to plant 5 is added with uniform variation and in the same quantity in each group, while the quantities of the other salts, although constant within a group, are not constant within all

TABLE 1

WEIGHT IN GRAMS OF SALTS ADDED TO EACH POT CONTAINING 2000 GRAMS OF SAND

(In the following table the roman numerals indicate the series numbers, and the letters are those of the corresponding groups.)

Pot No.	NaNO$_3$, grams	Ca(H$_2$PO$_4$)$_2$.H$_2$O, grams	K$_2$SO$_4$, grams	MgSO$_4$.7 H$_2$O, grams	Total concentration, grams	Pot No.	NaNO$_3$, grams	Ca(H$_2$PO$_4$)$_2$.H$_2$O, grams	K$_2$SO$_4$, grams	MgSO$_4$.7 H$_2$O, grams	Total concentration, grams
IA1	.02	1.2	2.4	.96	4.58	IIC1	1.5	.02	1.2	.48	3.20
IA2	.2	1.2	2.4	.96	4.76	IIC2	1.5	.10	1.2	.48	3.28
IA3	1.0	1.2	2.4	.96	5.56	IIC3	1.5	.20	1.2	.48	3.38
IA4	2.0	1.2	2.4	.96	6.56	IIC4	1.5	1.0	1.2	.48	4.18
IA5	3.0	1.2	2.4	.96	7.56	IIC5	1.5	2.0	1.2	.48	5.18
IB1	.02	.8	1.6	.64	3.06	IID1	.75	.02	.6	.24	1.61
IB2	.2	.8	1.6	.64	3.24	IID2	.75	.1	.6	.24	1.69
IB3	1.0	.8	1.6	.64	4.04	IID3	75	.2	.6	.24	1.79
IB4	2.0	.8	1.6	.64	5.04	IID4	.75	1.0	.6	.24	2.59
IB5	3.0	.8	1.6	.64	6.04	IID5	.75	2.0	.6	.24	3.59
IC1	.02	.6	1.2	.48	2.30	IIIA1	3.0	1.2	.02	.96	5.18
IC2	.2	.6	1.2	.48	2.48	IIIA2	3.0	1.2	.10	.96	5.26
IC3	1.0	.6	1.2	.48	3.28	IIIA3	3.0	1.2	.20	.96	5.36
IC4	2.0	.6	1.2	.48	4.28	IIIA4	3.0	1.2	1.0	.96	6.16
IC5	3.0	.6	1.2	.48	5.28	IIIA5	3.0	1.2	2.0	.96	7.16
ID1	.02	.3	.6	.24	1.16	IIIB1	2.25	.8	.02	.64	3.71
ID2	.2	.3	.6	.24	1.34	IIIB2	2.25	.8	.10	.64	3.79
ID3	1.0	.3	.6	.24	2.14	IIIB3	2.25	.8	.20	.64	3.89
ID4	2.0	.3	.6	.24	3.14	IIIB4	2.25	.8	1.0	.64	4.69
ID5	3.0	.3	.6	.24	4.14	IIIB5	2.25	.8	2.0	.64	5.69
IIA1	3.0	.02	2.4	.96	6.38	IIIC1	1.5	.6	.02	.48	2.60
IIA2	3.0	.10	2.4	.96	6.46	IIIC2	1.5	.6	.10	.48	2.68
IIA3	3.0	.20	2.4	.96	6.56	IIIC3	1.5	.6	.20	.48	2.78
IIA4	3.0	1.0	2.4	.96	7.36	IIIC4	1.5	.6	1.0	.48	3.58
IIA5	3.0	2.0	2.4	.96	8.36	IIIC5	1.5	.6	2.0	.48	4.58
IIB1	2.25	.02	1.6	.64	4.51	IIID1	.75	.3	.02	.24	1.31
IIB2	2.25	.10	1.6	.64	4.59	IIID2	.75	.3	.10	.24	1.39
IIB3	2.25	.20	1.6	.64	4.69	IIID3	.75	.3	.20	.24	1.49
IIB4	2.25	1.0	1.6	.64	5.49	IIID4	.75	.3	1.0	.24	2.29
IIB5	2.25	2.0	1.6	.64	6.49	IIID5	.75	.3	2.0	.24	3.29

the groups of a series. Thus I A 5, I B 5, I C 5, and I D 5 each contained 3 grams NaNO₃, but the content of each pot in K₂SO₄ was 2.4, 1.6, 1.2, and 0.6 grams, respectively; hence the balance between NaNO₃ and K₂SO₄ is very different in each of the four pots. Table 1 shows the distribution of the salts in the three series and the total concentration in grams of the salts in each pot. The total quantity of nutrient salts was added to the sand at the beginning of the experiment.

The plants were placed in the sand June 15 and were harvested about November 1, the tops and roots being kept for the determination of dry weight.[20] It will be seen that the plant was allowed sufficient time to complete its natural period of growth, thus permitting certain observations of a quantitative nature as recorded in table 2.

PHYSIOLOGICAL EFFECT OF NITROGEN

DISTRIBUTION OF SALTS IN SERIES I

In series I nitrogen as NaNO₃ was the salt which was used in the same weights in all of the four groups A, B, C, and D, being present in pots 1 to 5 as follows: 0.01 g. (.001 per cent), 0.2 g. (.01 per cent), 1.0 g. (.05 per cent), 2.0 g. (.1 per cent), 3.9 g. (.15 per cent). The maximum weights of other salts were Ca(H₂PO₄)₂, 1.2 g.; K₂SO₄, 2.4 g.; MgSO₄, 0.96 g., in group A, while the minimum quantity of these salts as added in group D was 0.3 g., 0.6 g., and 0.24 g., respectively. The total concentration in this series ranged from 1.16 g. in I D 1 to 7.56 g. in I A 5.

HEIGHT IN SERIES I

The height of each plant was measured at two different periods. The first measurement was made when the majority of the plants were just beginning to show the first signs of flower-bud formation. The second measurement was taken five or six weeks later, when most of the plants were in full bloom. The final height of the five plants in each group is shown graphically

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[20] An accident to the roots while drying prevented the collection of further data on their dry weight.

TABLE 2

SUMMARY OF QUALITATIVE AND QUANTITATIVE DATA FOR EACH PLANT

(In the following table the roman numerals indicate the series numbers, and the letters are those of the corresponding groups.)

Pot No.	Height, cm.	Leaf length, cm.	Leaf width, cm.	Number leaves	Number flowers	Dry weight tops, gms.
IA1	2.5	7.6	3.7	6.	0.	1.12
IA2	4.5	9.6	4.7	7.	0.	1.60
IA3	8.	12.1	6.2	10.5	0.	1.56
IA4	57.5	13.8	9.5	17.	25.5	......
IA5	45.5	20.8	10.2	17.5	24.	7.83
IB1	5.5	9.5	4.9	7.5	0.	1.29
IB2	3.5	8.6	4.1	7.	0.	1.40
IB3	8.	12.1	5.5	9.	1.	2.17
IB4	78.	18.8	9.5	17.5	29.	8.57
IB5	49.	19.9	10.1	17.5	21.	7.96
IC1	3.5	8.8	4.3	6.5	0.	.74
IC2	2.5	8.3	4.3	6.	0.	.79
IC3	4.5	11.2	5.6	7.	0.	1.65
IC4	94.	19.5	9.7	17.15	31.5	......
IC5	74.	18.7	9.1	18.	29.	9.24
ID1	6.5	10.5	5.4	7.	0.	1.65
ID2	17.5	12.7	6.3	9.5	0.	1.53
ID3	59.5	15.8	7.8	15.	8.5	5.86
ID4	91.5	14.6	7.7	19.	34.5	11.12
ID5	66.5	17.3	8.6	18.5	21.5	7.60
IIA1	15.	12.9	6.4	12.	0.	2.09
IIA2	55.	18.5	8.4	15.5	14.5	6.21
IIA3	69.5	18.9	9.4	16.5	22.5	8.75
IIA4	87.	19.2	9.7	16.5	25.5	8.58
IIA5	73.	18.9	9.3	16.5	29.	8.60
IIB1	21.	13.1	6.1	12.	0.	2.71
IIB2	35.5	15.3	7.3	14.5	4.5	3.82
IIB3	43.	15.	7.4	14.	9.5	4.1
IIB4	97.	18.3	9.3	18.5	37.	9.3
IIB5	74.5	18.6	9.6	17.	23.5	7.76
IIC1	13.5	12.2	5.9	11.	0.	2.73
IIC2	27.5	13.9	6.6	12.	3.	3.22
IIC3	101.	16.5	8.2	17.5	34.5	8.20
IIC4	90.	17.3	8.9	17.	32.	8.66
IIC5	78.	17.1	8.3	18.	26.5	7.88
IID1	18.	12.8	6.	11.5	2.5	2.47
IID2	64.5	14.8	7.4	15.5	15.	5.83
IID3	74.	15.5	7.6	16.	19.5	6.27
IID4	83.5	14.2	7.5	17.5	28.	7.60
IID5	86.	13.9	7.2	17.	19.	6.75
IIIA1	56.5	16.7	8.0	14.5	6.5	4.65
IIIA2	82.5	20.	10.1	16.5	27.	7.88
IIIA3	62.	20.7	9.6	17.5	14.	6.97
IIIA4	74.	20.2	10.	17.	20.5	10.53
IIIA5	63.	22.1	10.5	17.	24.	8.11

TABLE 2—(*Continued*)

Pot No.	Height, cm.	Leaf length, cm.	Leaf width, cm.	Number leaves	Number flowers	Dry weight tops, gms.
IIIB1	81.5	19.9	10.1	17.	22.	8.18
IIIB2	87.	20.3	10.	17.5	24.	5.87
IIIB3	94.5	18.3	9.4	17.5	31.	8.4
IIIB4	83.	19.1	9.7	18.	26.5	4.86
IIIB5	77.5	18.8	9.7	17.	39.5	8.42
IIIC1	89.	18.	9.	17.	18.	6.58
IIIC2	102.	17.7	8.8	17.5	22.5	8.57
IIIC3	109.	17.4	8.9	18.	23.	9.4
IIIC4	88.5	18.5	9.2	17.5	25.	7.66
IIIC5	79.	17.2	8.8	18.	26.5	8.68
IIID1	89.	16.4	8.2	17.	14.	5.6
IIID2	103.5	15.1	7.8	18.	17.5	7.27
IIID3	100.5	15.9	7.8	17.5	16.5	6.96
IIID4	90.	16.5	8.2	17.5	23.	6.75
IIID5	66.5	17.5	8.7	17.5	19.	6.36

in figure 1. As two plants were given similar treatment in each case, the height as noted in table 2 is the mean of the height measurements of these two plants.
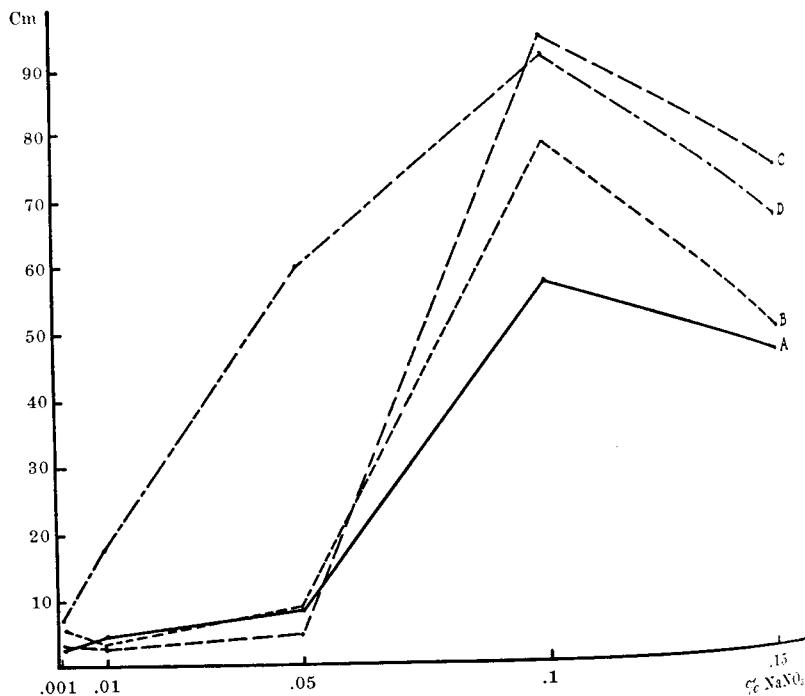
Fig. 1.—Graph showing the influence upon height of equal quantities of $NaNO_3$ in the different groups of series I.

The effect of increasing the quantity of nitrogen from plant 1 to plant 4 is marked in all groups. In every group plant 5 is not so tall as plant 4 (pl. 5), hence it would seem that the optimum nitrogen supply for tobacco growing in sand cultures, with height as an index, is somewhere near 0.1 per cent of NaNO₃, calculated on the basis of the dry weight of the sand.
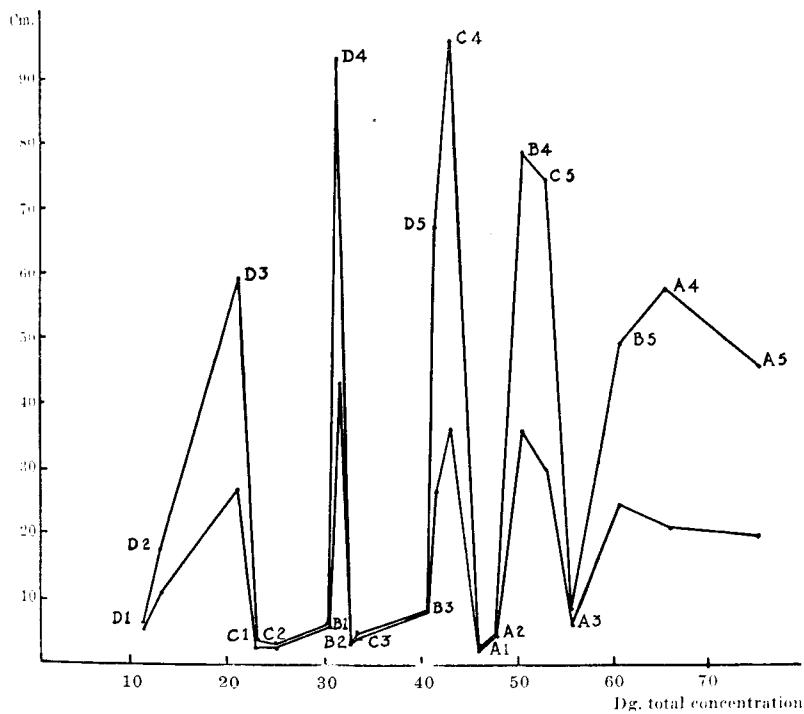
Fig. 2.—Graph showing the influence of total concentration upon height in series I.

There is slight variation in the first three plants of groups A, B, and C, showing that change in the total concentration of the solution within these limits does not affect the characters of the plants to any great extent. This, however, does not apply to group D, in which the total concentration is low (1.16 to 4.14 g.), for plants 2 and 3 are far superior to the corresponding plants of the other groups, although the nitrogen content is exactly the same. When the nitrogen content is at or near the

optimum the influence of concentration on height is exhibited
in a more uniform manner, as shown in plants 4 and 5 of all
groups (pl. 6). Plants growing in the solution of lower concen-
tration, in general, are taller than those growing in the solutions
of higher concentration.

The influence of total concentration upon height of plant
when taken in connection with optimum and deficient nitrogen
supply is indicated in figure 2, which shows a curve for each of
the two measurements made on each plant, the upper curve being
plotted from the last measurements taken. This curve is espe-
cially interesting since it shows the influence of nitrogen as a
prime factor in growth in solutions which are of approximately
the same concentration. Thus in I D 4 and I B 1, where the
total concentrations are 3.14 g. and 3.06 g., the heights of the
two plants are 91.5 cm. and 5.5 cm. Such a large difference can
be due in this case only to the lack of nitrogen in I B 1, since
there is present a considerable excess of the other nutrients
required (pl. 7).

A study of the early and late height curves shows that the
plant responded very early to the amount of salts available, as
is indicated by the similarity of the early curve to that based
upon the later measurements. The greatest final height is at-
tained, as was to be expected, through the continuous growth
of those plants which had sufficient nitrogen, while the growth
of the under-nourished plant was decidedly retarded. Thus at
the end of the growing season the differences in height between
the two groups became more marked as the time of complete
maturity drew near. Attention is called to this fact since it is
not an uncommon practice in growing plants in water cultures
to harvest them before maturity. While these plants might give
an index of the influence of the culture solution on growth, they
would not give a true value for the nutritive function of the
solution, since increase might persist for a considerable time in
solutions of optimum nutritive value while plants growing in an
unfavorable medium would be practically at a standstill.

Dry Weight in Series I

A comparison of the curves for height (fig. 1) and for dry weight (fig. 3) shows that in a general way height is an index to the dry weight. This fact is more marked in this series than in either series II or III since the plants were more uniform throughout the series, being uniformly stocky where the height was above 40 cm. In the other groups some of the plants were
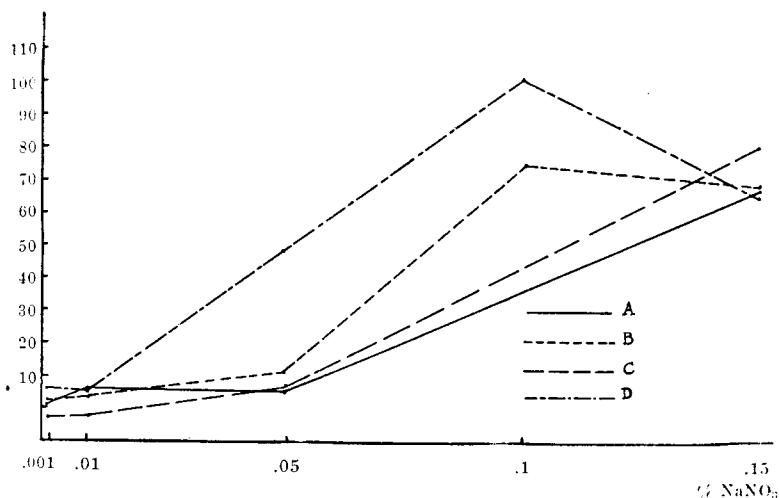
Fig. 3.—Graph showing influence of equal quantities of $NaNO_3$ in the different groups of series I upon dry weight of tops.

tall and very spindly (pl. 15), and there was a marked decrease in the length and width of leaf, which would, of course, lower the dry weight. The height measurements even on a plant of the habit of the tobacco cannot be taken alone as an indication of the nutritive value of a solution, a fact which has been shown to hold true to a much more noticeable extent in such plants as wheat, which will stool more in some cultures than in others without perceptible differences in height.

The effect of the concentration is evidenced in the curve for group D, which is much higher for plants 3 and 4 than for plants of like number in any other groups. Had it been possible to take

the dry weight for plant I C 4 this weight would probably have been slightly greater than that of I D 4 (see table 2), making the curves correspond to those for height.

THE INFLUENCE OF THE CULTURE SOLUTION ON FLOWER PRODUCTION

Our information concerning factors which may influence flower formation is very incomplete. Vochting[21] has demonstrated that light intensity is a factor in flower development in *Mimulus,* and numerous other plant physiologists have found that a more or less marked influence on flower formation could be correlated with some external factor. The relation to the formation of flowers of nutrient salts in the medium in which growth takes place seems never to have been studied in any thoroughgoing manner. Mobius[22] found that certain *Graminea* flowered better on dry soil and on soil low in nutrient elements than on soil rich in nutrients and where water supply was abundant. Jost[23] thinks that the fact that root pruning increases flower production may be thus explained, since there is a lowering of the absorptive capacity of the tree for inorganic salts. There has been also a general opinion, which is not fully justified, that any condition which will cause marked vegetative development will retard flower production. The experiment herein reported has presented an opportunity for a study of the influence of the composition and concentration of the solution upon flower production.

In the plant used in this experiment the flowers fall soon after opening, leaving a scar upon the inflorescence stock.[24] At the end of the growing season the number of flowers produced by each plant was determined by counting these scars (see table 2). The total number of flowers produced by each plant is shown diagrammatically in figure 4.

21 Vochting, Jahrb. f. wiss. Bot., vol. 25, p. 149, 1893.
22 Mobius, Beitr. z. Lehre v. d. Fortpflanzung d. Gewachse, Jena, 1897.
23 Jost, Lectures on plant physiology, p. 364, 1907.
24 Goodspeed and Ayres, Univ. Calif. Publ. Bot., vol. 5, no. 9, 1916.
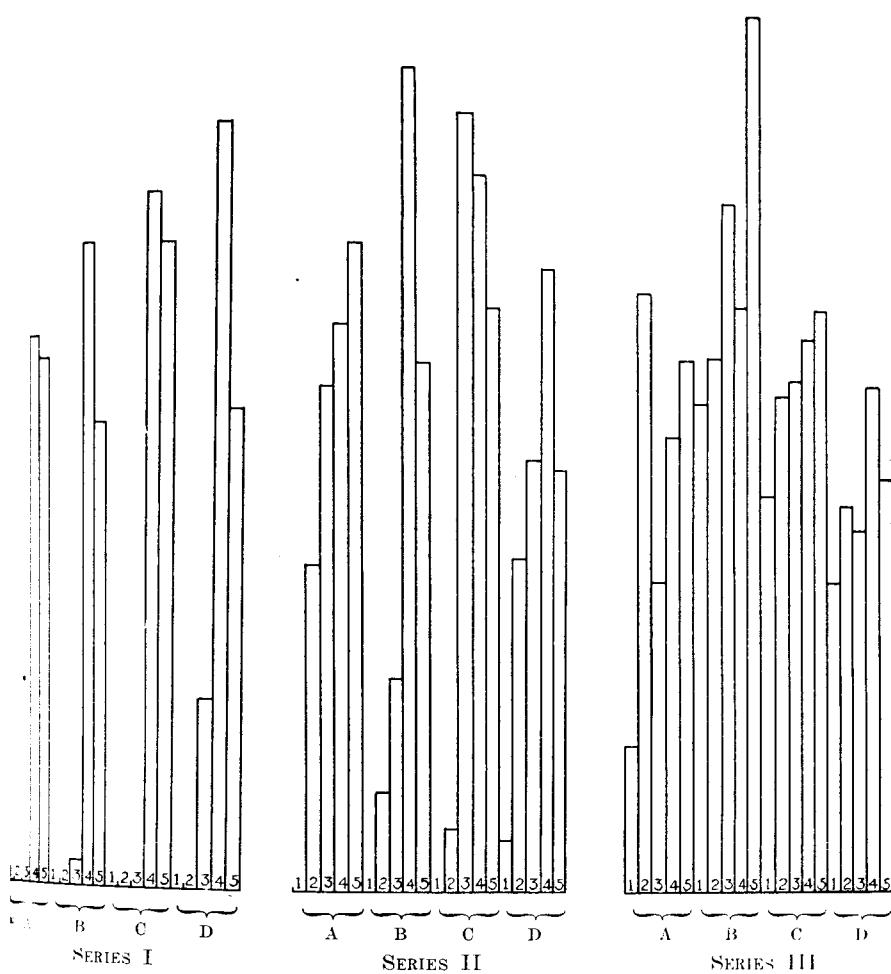
Fig. 4.—Diagrammatic representation of the number of flowers produced
by each plant in series I, II, and III.

FLOWER PRODUCTION IN SERIES I

The nitrogen supply is seen to have a very definite influence
upon flower production.   In series I no flowers were produced
by plants 1 and 2 of any group and in only two groups were
any flowers produced by plant 3, showing definitely that unless
nitrogen is present in excess of 0.05 per cent as $NaNO_3$ the under-
nourished tobacco plant will not flower.   Flower production in

general corresponded to vegetative vigor, the plant exhibiting maximum vegetative growth producing the largest number of flowers. Here again the influence of the total concentration of the solution was apparent in the flower yield in the various groups, which increased as the concentration decreased.
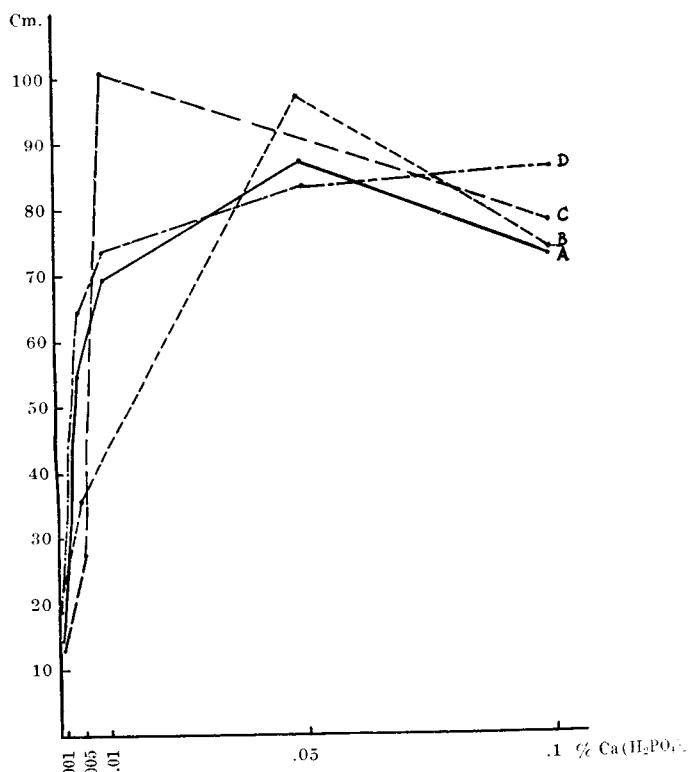
Fig. 5.—Graph showing the influence upon height of equal quantities of $Ca(H_2PO_4)_2$ in the different groups of series II.

PHYSIOLOGICAL EFFECT OF PHOSPHORUS

DISTRIBUTION OF SALTS IN SERIES II

In series II a study was made of the influence of phosphorus added as $Ca(H_2PO_4)_2$. This salt was present in the same quantity in all groups A, B, C, and D, the quantity in each of the pots 1 to 5 being 0.02 g. (.001 per cent), 0.1 g. (.005 per cent), 0.2 g. (.01 per cent), 1.0 g. (.05 per cent), 2.0 g. (.1 per cent),

respectively.   The maximum weights of the other salts were $NaNO_3$, 3 g.; K_2SO_4, 2.4 g.; $MgSO_4$, 0.96 g., in group A, while the minimum quantities of these salts as added in group D were 0.75 g., 0.6 g., and 0.24 g., respectively.   The total concentration in this series ranged from 1.61 g. to 6.38 g.
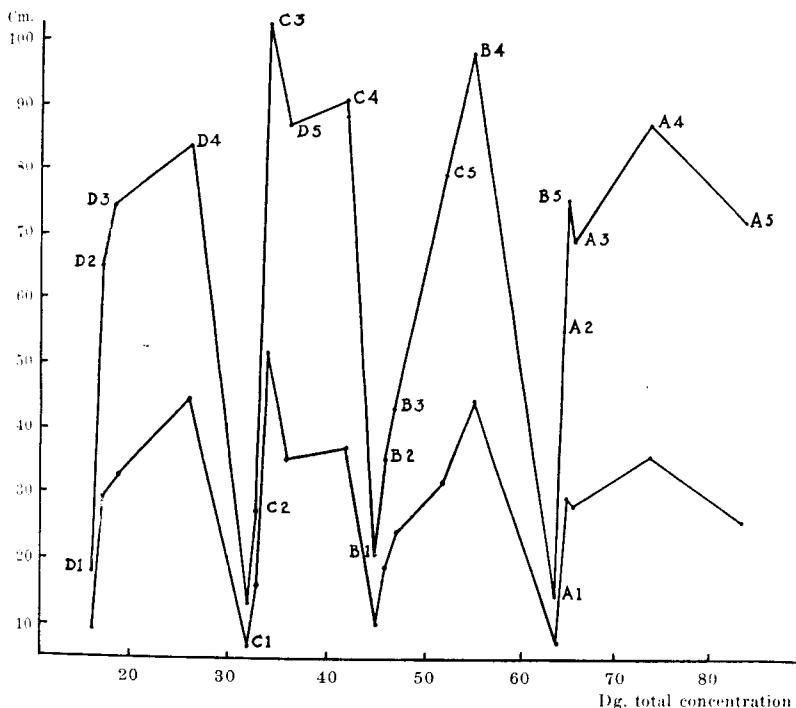
Fig. 6.—Graph showing the influence of total concentration upon height in series II.

HEIGHT IN SERIES II

Figure 5 shows the height curves for the five plants of each of the four groups in this series.   There is clear indication that the optimum phosphorus supply lies somewhere between .05 per cent and .01 per cent of $Ca(H_2PO_4)_2$, the height of plant 4 being greatest when all groups are considered.   The difference in height between plants 4 and 5 is not great in any group.   The effect of increasing the quantity of $Ca(H_2PO_4)_2$ is clearly seen in plants 1, 2, 3, and 4 of groups A, B, and D (pl. 8).   The effect of total

concentration in this series is not so marked as in series I, but is slightly evidenced in the somewhat better growth of some of the plants in groups C and D as compared with plants in groups A and D (pl. 9). The height of the plants at two different periods in their growth was taken in this series at the same time that the measurements were taken in series I and plotted against total concentration (fig. 6). The total concentration of salts in the solution is here, as in series I, of secondary importance when one element is present in insufficient amount, as will be seen (pl. 6) when plant II C 1 (3.20 g.) is compared with II C 3
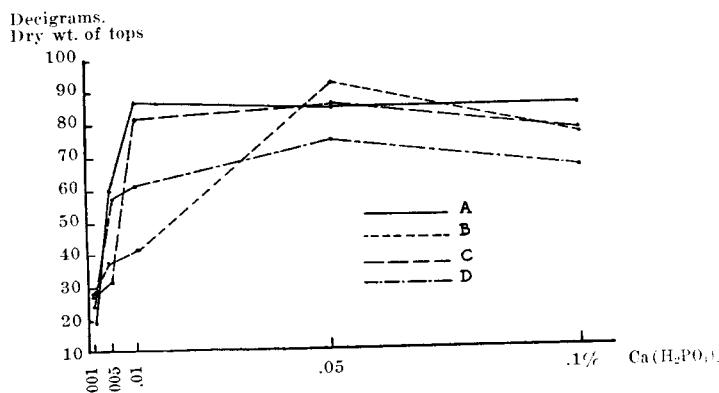
Fig. 7.—Graph showing the influence on dry weight of tops of equal quantities of $Ca(H_2PO_4)_2$ in the different groups of series II.

(3.38 g.). While the total concentration is practically the same and the total quantity of each of the other salts is the same the $Ca(H_2PO_4)_2$ in II C 3 is ten times the quantity of the same salt in II C 1.

DRY WEIGHT IN SERIES II

A comparison of height (fig. 5) and dry weight curves (fig. 7) for tops in this series shows that height here is not an accurate index to dry weight. Thus group A gave the greatest total dry weight, while the greatest total height of plants occurred in group D, a fact which is explicable since very serious injury resulting in a spindly habit was shown by many plants in the D group, as will be pointed out later in the discussion of injury due to the improper balance of salts in the solution.

FLOWER PRODUCTION IN SERIES II

The total number of flowers produced in this series was larger than in series I, due largely to the fact that there was less stunted growth in plants 1, 2, and 3 of each group, for which an ample supply of nitrogen was available. Plants II A 1, II B 1, and II C 1 did not produce any flowers. The greatest number of flowers was formed in group C and the greatest yield of any one plant was given by II B 5. The flower yield in each group is definitely related to the general character of the plant as mentioned above in connection with series I.

PHYSIOLOGICAL EFFECT OF POTASSIUM

DISTRIBUTION OF SALTS IN SERIES III

The plants in series III were grown to study the physiological influence of various quantities of potassium added as K_2SO_4 in the presence of a sufficient supply of other nutrient salts, following the same plan as outlined above for the variation of nitrogen and phosphorus in series I and II. K_2SO_4 was present in the same weight in each of the four groups A, B, C, and D, the quantities added to each of the pots 1 to 5 being 0.02 g. (.001 per cent), 0.1 g. (.005 per cent), 0.2 g. (.01 per cent), 1.0 g. (.05 per cent), and 2.0 g. (.1 per cent). The maximum weights of the other salts were $NaNO_3$, 3 g.; $Ca(H_2PO_4)_2$, 1.2 g.; $MgSO_4$, 0.96 g., in group A. In group D the minimum quantities of these salts were 0.75 g., 0.3 g., and 0.24 g., respectively. The total concentration in this series varied from 1.31 g. to 7.16 g.

HEIGHT IN SERIES III

No plants in this series were less than 50 cm. high, due to the fact that the two nutrient elements, nitrogen and phosphorus, which in the order named are of first importance as growth factors, were present in sufficient quantity to insure considerable growth (pl. 7). Only a small quantity of K_2SO_4 (.005 to .01 per cent) was required in this series to give plants of maximum height, hence the curves show a downward trend in all plants after either plant 2 or plant 3 in each group (fig. 8, also pl. 12). Thus it is evident that there is a toxic effect of an excess of potassium, irrespective of the total concentration of the solution.

The influence of total concentration is again plainly seen in this series. Plate 13 shows plant 1 of each of the groups A, B, C, and D. As the total concentration decreases from A to C there is a steady increase in the vigor of the plant as judged by height. Curves in figure 9 indicate this general tendency to an increase of height with a decrease in the total concentration of the solution.

DRY WEIGHT IN SERIES III

As in series I and II, the dry-weight curves (fig. 10) do not correspond with the height curves (fig. 8). The greatest dry weight of any plant was that of III A 4, which was not so tall as the other plants of like number. The low dry weight of III B 4 is especially noticeable. A comparison of the two dry-weight curves for the A and B groups shows a very peculiar effect of K_2SO_4 in solutions of different balance. In each case where the group A curve is high, the group B curve is low, a fact which also applies to plants 3, 4, and 5 in the A and C groups. That this should occur with such regularity is rather remarkable and no satisfactory explanation can as yet be found to account for this situation. It is evident that the physiological balance of salts in the solution is dependent upon the concentration, as has been shown by McCool,[25] Gile,[26] Tottingham,[27] and Shive.[28]

FLOWER PRODUCTION IN SERIES III

The more vigorous growth of plants in this series gave a greater total yield of flowers than either of the other two series. This was to be expected from the result of series I and II, where the flower yield was shown to be definitely related to the general vigor of the plants. The production of flowers in this series differs, however, from that in the other series. An increase of K_2SO_4, while in general depressing the total height of the plant, when added in excess of .01 per cent gave a higher flower yield. Thus in group C there is steady increase in the number of flowers produced which corresponds to the increase of K_2SO_4. The

[25] McCool, Cornell Agric. Exp. Sta. Mem., vol. 2, pp. 121–170, 1913.
[26] Gile, Porto Rico Agric. Exp. Sta. Bull. 12.
[27] *Loc. cit.*
[28] *Loc. cit.*
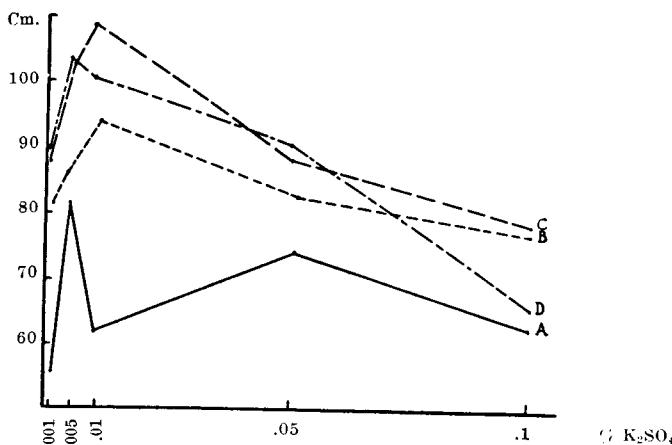
Fig. 8.—Graph showing the influence upon height of equal quantities of K_2SO_4 in the different groups of series III.
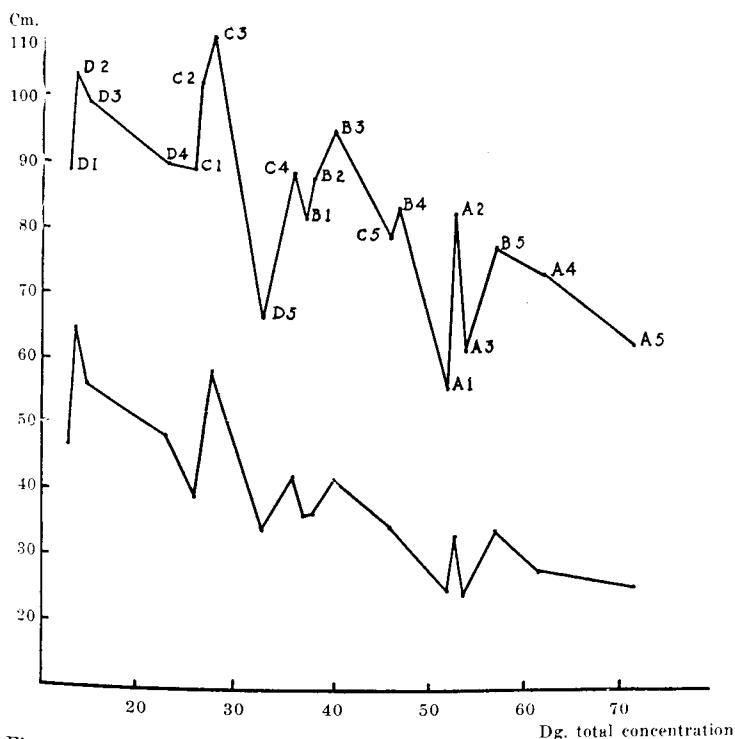
Fig. 9.—Graph showing the influence upon height of total concentration in series III.

greatest flower production occurred in group B, and plant 5 of this group produced a larger number of flowers than any other plant in any series.

INJURY DUE TO EXCESS OR DEFICIENCY OF NUTRIENT SALTS

The deficiency or excess of certain elements will cause injury which is very characteristic. Gris as early as 1843 showed that chlorosis was caused by a lack of iron in the nutrient solution. Nitrogen starvation likewise has long been known to cause chlorosis, a condition which may also result from an excess of soluble
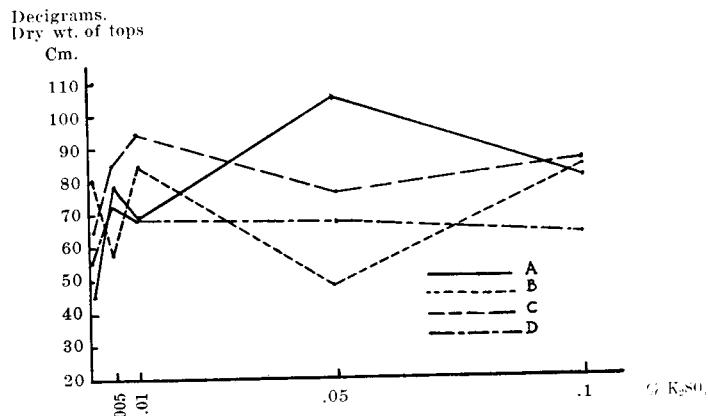
Fig. 10.—Graph showing the influence upon dry weight of tops of equal quantities of K_2SO_4 in the different groups of series III.

phosphate.[29] Magnesium starvation results in injury to the chlorophyll bodies, and in excess is harmful unless antagonized by calcium.[30] Other physiological disturbances not so well established as these mentioned have been considered to be associated with a deficiency or excess of nutrient elements.

The most marked indication of the fact that certain cultures in this experiment did not furnish a normal medium for growth was seen in the chlorosis which is so characteristic of plants grown in solutions which are deficient in nitrogen. This type of injury was uniformly present in all cultures containing 1.0 g. or less of $NaNO_3$, but was especially marked in series I, plants 1, 2, and 3, of all groups. It is not possible to draw a sharp

[29] Crone, Sitzungsber Neiderrhein. Ges. Nat.- und Heilk, Bonn, 1902. pp. 167–173.
[30] Loew and May, U. S. Dept. Agric. Bur. Plant Ind. Bull. 1, 1901.

line which will clearly segregate the injury to the various plants of a large series of this kind into well-defined groups since there is always more or less overlapping. An attempt was made, however, to divide the plants into groups which would show in each case a characteristic type of injury.

(*a*) This group was made up of plants which were very much stunted, being less than 8 cm. in height and in every case showed a marked chlorosis which was clearly attributed to a low supply of nitrogen. The plants in this group were I A 1, I A 2, I A 3, I B 1, I B 2, I B 3, I C 1, I C 2, I C 3, I D 1.

(*b*) This group was somewhat taller, from 13 to 21 cm. high, but clearly stunted in growth. These plants showed less chlorosis, since nitrogen was present in sufficient quantity to provide close to the optimum supply in all cultures with the exception of II D I and I D 2, where there was a distinct chlorosis due to the low nitrogen supply. Plants showing this type of injury were II A 1, II B 1, II C 1, II D 1, I D 2.

(*c*) Plants in this group showed a more serious type of injury than any of the other plants. They were more than 40 cm. in height, but were very spindly (pl. 15). The whole plant showed marked chlorosis, which affected the lower leaves most severely and soon resulted in their death. This type of plant was found in cultures I D 3, II B 2, II B 3, II C 2, II D 2, II D 3, II D 4, III D 1, III D 2, III D 3, III D 4, and III D 5.

(*d*) The plants of this group were decidedly more vigorous than those of the preceding groups, as indicated by their increased height and better color. Indeed, they seemed to be perfectly normal. The following cultures were classed in this group: I C 4, I D 4, II C 3, II C 4, II D 5, III A 1, III A 2, III A 3, III B 1, III B 2, III B 3, III C 1, III C 2, III C 3, III C 4, III C 5. The following plants were even better in appearance than those just named: I A 4, I A 5, I B 4, I B 5, I C 5, I D 5, II A 2, II A 3, II A 4, II A 5, II B 4, II B 5, II C 5, III A 4, III A 5, III B 4, III B 5.

A study of the above grouping indicates that chlorosis was present wherever the nitrogen content was low, as was to be expected. The spindly growth characteristic of groups II D and III D may also be due to the low supply of nitrogen. It seems

that the injury which was so marked in series II must be in some way associated with the calcium-magnesium content in solutions which were not properly balanced. No definite calcium-magnesium ratios can be found which are responsible for the injury which occurred in this series. Twenty different calcium-magnesium ratios ranging from 0.035 to 3.54 occur in the series, and both plants which were normal and plants which were seriously injured were found in cultures in which the calcium-magnesium ratio was low as well as in cultures where this ratio was high. No definite conclusions can be drawn in this connection, however, since the other variables present complicate the situation so that the injury cannot be said with certainty to be associated with an improper balance between the calcium and magnesium.

TABLE 3

Summary of Complete Experiments

Grouped in such a manner that comparison can be made with special reference to the influence of concentration and balance of the solution upon crop and flower production. The calculation of the per cent total concentration is based on the assumption that the salts are all dissolved in the quantity of water held by 2000 grams of sand when saturated. To get this value in parts per million, multiply the total concentration in grams by 227.2. The real concentration would be much greater than these values would indicate, since the sand was not kept saturated.

Series I

	$NaNO_3$, grams	$NaNO_3$, per cent	$Ca(H_2PO_4)_2$ grams	K_2SO_4 grams	$MgSO_4$ grams	Total, grams	Total concentration, per cent in solution	Height, cm	Tops (dry), grams	Number of flowers
IA1	.02	.001	1.2	2.4	.96	4.58	1.04	2.5	1.12	0.
IB1	.02	.001	.8	1.6	.64	3.06	.69	5.5	1.29	0.
IC1	.02	.001	.6	1.2	.48	2.30	.52	3.5	.74	0.
ID1	.02	.001	.3	.6	.24	1.16	.26	6.5	1.65	0.
IA2	.2	.01	1.2	2.4	.96	4.76	1.08	4.5	1.6	0.
IB2	.2	.01	.8	1.6	.64	3.24	.73	3.5	1.40	0.
IC2	.2	.01	.6	1.2	.48	2.48	.56	2.5	.79	0.
ID2	.2	.01	.3	.6	.24	1.34	.30	17.5	1.53	0.
IA3	1.0	.05	1.2	2.4	.96	5.56	1.26	8.	1.56	0.
IB3	1.0	.05	.8	1.6	.64	4.04	.91	8.	2.17	1.
IC3	1.0	.05	.6	1.2	.48	3.28	.74	4.5	1.65	0.
ID3	1.0	.05	.3	.6	.24	2.14	.48	59.5	5.86	8.5
IA4	2.0	.1	1.2	2.4	.96	6.56	1.35	57.5	......	25.5
IB4	2.0	.1	.8	1.6	.64	5.04	1.14	78.	8.57	29.
IC4	2.0	.1	.6	1.2	.48	4.28	.97	94.	......	31.
ID4	2.0	.1	.3	.6	.24	3.14	.71	91.5	11.12	34.5
IA5	3.0	.15	1.2	2.4	.96	7.56	1.71	45.5	7.83	24.
IB5	3.0	.15	.8	1.6	.64	6.04	1.37	49.	7.96	21.
IC5	3.0	.15	.6	1.2	.48	5.28	1.20	74.	9.24	29.
ID5	3.0	.15	.3	.6	.24	4.14	.94	66.	7.60	21.5

SERIES II

	Ca(H₂PO₄)₂, grams	Ca(H₂PO₄)₂, per cent	NaNO₃ grams	K₂SO₄ grams	MgSO₄ grams	Total, grams	Total concentration, per cent in solution	Height, cm.	Tops (dry)	Number of flowers
IIA1	.02	.001	3.	2.4	.96	6.38	1.45	15.	2.09	0.
IIB1	.02	.001	2.25	1.6	.64	4.51	1.02	21.	2.71	0.
IIC1	.02	.001	1.5	1.2	.48	3.20	.72	13.5	2.73	0.
IID1	.02	.001	.75	.6	.24	1.61	.36	18.	2.47	2.5
IIA2	.10	.005	3.	2.4	.96	6.46	1.46	55.	6.21	14.5
IIB2	.10	.005	2.25	1.6	.64	4.59	1.04	35.5	3.82	4.5
IIC2	.10	.005	1.5	1.2	.48	3.28	.74	27.5	3.22	3.
IID2	.10	.005	.75	.6	.24	1.69	.38	64.5	5.83	15.
IIA3	.20	.01	3.	2.4	.96	6.56	1.49	69.5	8.75	22.5
IIB3	.20	.01	2.25	1.6	.64	4.69	1.06	43.	4.11	9.5
IIC3	.20	.01	1.5	1.2	.48	4.18	.94	101.	8.20	17.5
IID3	.20	.01	.75	.6	.24	2.59	.58	74.	6.27	16.
IIA4	1.0	.05	3.	2.4	.96	7.36	1.67	87.	8.58	25.5
IIB4	1.0	.05	2.25	1.6	.64	5.49	1.24	97.	9.3	37.
IIC4	1.0	.05	1.5	1.2	.48	4.18	.95	90.	8.66	32.
IID4	1.0	.05	.75	.6	.24	2.59	.58	83.5	7.60	28.
IIA5	2.0	.1	3.	2.4	.96	8.36	1.90	73.	8.60	29.
IIB5	2.0	.1	2.25	1.6	.64	6.49	1.47	74.5	7.76	23.5
IIC5	2.0	.1	1.5	1.2	.48	5.18	1.17	78.	7.88	26.5
IID5	2.0	.1	.75	.6	.24	3.59	.81	86.	6.75	19.

SERIES III

	K₂SO₄, grams	K₂SO₄, per cent	NaNO₃ grams	Ca(H₂PO₄)₂ grams	MgSO₄ grams	Total, grams	Total concentration, per cent in solution	Height, cm.	Tops (dry)	Number of flowers
IIIA1	.02	.001	3.	1.2	.96	5.18	1.17	56.5	4.65	6.5
IIIB1	.02	.001	2.25	.8	.64	3.71	.84	81.5	8.18	22.
IIIC1	.02	.001	1.5	.6	.48	2.60	.59	89.	6.58	18.
IIID1	.02	.001	.75	.3	.24	1.31	.29	89.	5.56	14.
IIIA2	.1	.005	3.	1.2	.96	5.26	1.19	82.5	7.88	27.
IIIB2	.1	.005	2.25	.8	.64	3.79	.86	87.	5.87	24.
IIIC2	.1	.005	1.5	.6	.48	2.68	.60	102.	8.57	22.5
IIID2	.1	.005	.75	.3	.24	1.39	.31	103.5	7.27	17.5
IIIA3	.2	.01	3.	1.2	.96	5.36	1.21	62.	6.97	14.
IIIB3	.2	.01	2.25	.8	.64	3.89	.88	94.5	8.4	31.
IIIC3	.2	.01	1.5	.6	.48	2.78	.63	109.	9.4	23.
IIID3	.2	.01	.75	.3	.24	1.49	.33	100.5	6.9	16.5
IIIA4	1.0	.05	3.	1.2	.96	6.16	1.40	74.	10.53	20.5
IIIB4	1.0	.05	2.25	.8	.64	4.69	1.06	83.	4.86	26.5
IIIC4	1.0	.05	1.5	.6	.48	3.58	.81	88.5	7.66	25.
IIID4	1.0	.05	.75	.3	.24	2.29	.52	90.	6.75	23.
IIIA5	2.0	.1	3.	1.2	.96	7.16	1.62	63.	8.11	24.
IIIB5	2.0	.1	2.25	.8	.64	5.69	1.29	77.5	8.42	39.5
IIIC5	2.0	.1	1.5	.6	.48	4.58	1.04	79.	8.68	26.5
IIID5	2.0	.1	.75	.3	.24	3.29	.74	66.5	6.36	19.

THE ABSORPTION OF SALTS FROM THE CULTURE MEDIUM

The absorption by plants of salts from a solution is no doubt intimately related to the composition of the solution, since the intake of inorganic salts occurs only when the concentration of the solute outside the permeable protoplast is greater than that within. Hence the total osmotic concentration of a solution may affect the intake and storage of the salts from the solution.[31] The quantity of salts which are absorbed by the plant may also vary with the qualitative composition of the solution. Thus True and Bartlett[32] have shown that absorption from a solution of two or of three salts is more rapid than from a solution containing a single salt. It is evident that the factors which regulate absorption are very complex, and that this complexity increases with an increase in the number of different anions and cations in the solution. It is further evident that two methods may be followed with a view to ascertaining the quantities of salts absorbed. The ash of the plants may be analyzed or the residue of salts remaining in the culture may be determined. It has seemed desirable to attempt a study of absorption in the present case by means of the latter method.

METHOD OF ANALYSIS

The small quantities of salts added to each pot made the acid-extraction method undesirable, since the large quantities of sand required to give weighable precipitates would have been extremely hard to dehydrate, thus introducing a considerable source of error. For this reason the colorimetric method of analysis[33] was used in this work. An exception was made in the determination of calcium, which was made by the usual volumetric method. The sulphur was determined gravimetrically as $BaSO_4$. A water extract was prepared from 250 g. of sand by leaching with successive small portions of distilled water until

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[31] Livingston, The rôle of diffusion and osmotic pressure in plants. Chicago, 1903.

[32] True and Bartlett, U. S. Dept. Agric. Bur. Plant Ind. Bull. 231, 1912; and Am. Jour. Bot., vol. 2, pp. 255–278, 311–323, 1915, vol. 3, pp. 47–58, 1916.

[33] Schreiner and Failyer, U. S. Dept. Agric. Bur. Soils, Bull. 31, 1906.

500 c.c. had been used. The filter containing the sand was then allowed to stand for about fifteen hours, and the sand was leached with another 500 c.c. portion of water. The filtrate was evaporated to dryness, the residue dehydrated at 100° C, and strongly ignited in a platinum dish to destroy organic matter. The residue was then dissolved in hot water and made up to definite volume from which aliquot portions were taken for analysis. A 2000 g. sample of the washed sand used in the experiment gave by this method the following analysis:

N	K	P	Mg	Ca	S
00.	33.6	5.2	66.4	2.4	15.6 milligrams

In this analysis, as well as in all the following analyses, the statement made is for the total weight in milligrams of the element contained in 2000 g. of sand, which was the quantity contained in each pot. Table 4 gives a summary of the analysis of each of the sixty samples of sand used. The total quantity of each element present, calculated from the quantities of salts added plus the quantity in the original sand, is given, as well as the number of milligrams of the element missing from the pot at the end of the growing season. This latter value is the difference between the total weight of the elements present and the residue as shown by the analysis of the water extract. The difference thus obtained represents the quantity of the element absorbed by the plant and adsorbed by the sand particles. It must be admitted that it is not known just how great a factor adsorption may be in the case of this sand.

DISCUSSION OF RESULTS

In series I no nitrogen as nitrate remained in pots 1, 2, 3, and 4 of groups A, B, and C. In group D there is a small residue of nitrogen in spite of the fact that the total crop production was greatest in this group. The concentration of the solution clearly affects the economical use of nitrogen, a fact which in general is also indicated in series II and in series III. It is especially noticeable that there is a much larger quantity of nitrogen left in series III D than in either series I D or II D. The total crop production for group III D was better than that of the D group

TABLE 4

SHOWING IN MILLIGRAMS THE WEIGHT OF EACH OF THE ELEMENTS N, P, K, MG, CA, AND S IN EACH POT (2000 GRAMS OF SAND) AT THE BEGINNING OF THE EXPERIMENTS AND THE WEIGHT OF EACH ELEMENT REMAINING AT THE END OF THE GROWING SEASON. THE DIFFERENCE REPRESENTS THE WEIGHT OF THE ELEMENT USED IN THE GROWTH OF THE PLANT OR HELD BY ADSORPTION BY THE SAND PARTICLES.

(In the following table the roman numerals indicate the series numbers, and the letters are those of the corresponding groups.)

	N total	N remaining	N difference	P total	P remaining	P difference	K total	K remaining	K difference	Mg total	Mg remaining	Mg difference	Ca total	Ca remaining	Ca difference	S total	S remaining	S difference	Dry weight, grams
IA1	3.29	0.0	3.29	300.3	6.2	294.1	572.3	81.6	490.7	160.9	71.2	89.7	192.8	1.6	191.2	581.1	23.6	557.5	1.12
IA2	32.9	0.0	32.9	300.3	7.8	292.5	572.3	91.2	481.1	160.9	44.8	116.1	192.8	6.4	186.4	581.1	32.4	548.7	1.60
IA3	164.6	0.0	164.6	300.3	6.2	294.1	572.3	94.4	457.9	160.9	71.2	89.7	192.8	7.2	185.6	581.1	39.5	541.6	1.56
IA4	329.3	0.0	329.3	300.3	8.0	292.3	572.3	83.2	489.1	160.9	71.2	89.7	192.8	13.6	179.2	581.1	54.3	526.8	......
IA5	493.9	20.3	473.6	300.3	9.6	290.7	572.3	76.8	495.5	160.9	64.0	96.9	192.8	9.6	183.2	581.1	31.3	549.8	7.83
IB1	3.29	0.0	3.29	201.9	7.8	194.1	392.8	81.6	311.2	129.4	65.6	63.8	129.3	8.0	128.5	391.3	30.2	361.1	1.29
IB2	32.9	0.0	32.9	201.9	2.6	199.3	392.8	52.8	340.0	129.4	61.2	68.2	129.3	12.8	116.5	391.3	23.6	367.7	1.4
IB3	164.6	0.0	164.6	201.9	5.7	196.2	392.8	60.8	332.0	129.4	71.2	58.2	129.3	18.4	110.9	391.3	34.5	356.8	2.17
IB4	329.3	0.0	329.3	201.9	5.7	196.2	392.8	36.0	356.8	129.4	68.4	61.0	129.3	4.8	124.5	391.3	27.4	363.9	8.57
IB5	493.9	36.1	457.8	201.9	7.8	194.1	392.8	57.4	335.4	129.4	99.6	29.8	129.3	31.2	98.1	391.3	......	......	7.96
IC1	3.29	0.0	3.29	152.8	6.2	146.6	303.0	75.2	227.8	113.7	89.6	24.1	97.6	9.6	88.0	297.2	25.2	272.0	.74
IC2	32.9	0.0	32.9	152.8	5.0	147.8	303.0	80.0	223.0	113.7	106.8	6.9	97.6	19.2	78.4	297.2	38.4	258.8	.79
IC3	164.6	0.0	164.6	152.8	6.4	156.4	303.0	73.6	229.4	113.7	61.2	52.5	97.6	12.0	85.6	297.2	43.9	253.3	1.65
IC4	329.3	0.0	329.3	152.8	5.7	147.1	303.0	26.8	276.2	113.7	61.2	52.5	97.6	28.0	69.6	297.2	51.1	246.1	......
IC5	493.9	1.58	492.5	152.8	7.0	145.8	303.0	35.2	267.8	113.7	54.0	59.7	97.6	42.4	55.2	297.2	41.7	255.5	9.24
ID1	3.29	1.13	2.16	79.0	4.0	75.0	168.3	40.8	127.5	90.0	61.2	28.8	50.0	28.0	22.0	156.2	27.4	128.8	1.65
ID2	32.9	1.17	30.7	79.0	3.6	75.4	168.3	28.0	140.3	90.0	100.0	......	50.0	66.4	......	156.2	21.9	134.3	1.53
ID3	164.6	1.26	163.5	79.0	3.6	75.4	168.3	20.0	148.3	90.0	69.6	20.4	50.0	66.4	......	156.2	30.2	126.0	5.86
ID4	329.3	1.58	327.7	79.0	5.7	73.3	168.3	8.0	160.3	90.0	78.0	12.0	50.0	12.0	38.0	156.2	46.6	109.6	11.12
ID5	493.9	1.80	492.1	79.0	6.2	72.8	168.3	12.8	145.5	90.0	42.8	47.2	50.0	41.6	8.4	156.2	......	......	27.76
IIA1	493.9	1.67	492.2	10.1	2.6	7.5	572.3	38.4	533.9	160.9	78.0	82.9	5.6	22.4	......	581.1	21.4	559.7	2.09
IIA2	493.9	1.67	492.2	29.8	2.6	27.2	572.3	21.8	517.5	160.9	15.7	145.2	18.3	65.6	......	581.1	64.5	512.0	6.21
IIA3	493.9	27.1	466.8	54.4	6.5	47.8	572.3	56.0	516.3	160.9	126.8	34.1	31.1	12.8	18.3	581.1	65.0	115.0	8.73
IIA4	493.9	23.5	471.5	25.1	7.4	213.5	572.3	80.0	492.3	160.9	74.5	81.5	161.7	12.7	149.0	581.1	......	......	7.04

	N total	Σ N remain	N differ.	P total	Σ P remain	P differ.	K total	Σ K remain	K differ.	Mg total	Σ Mg remain.	Mg differ.	Ca total	Σ Ca remain.	Ca differ.	S total	Σ S remain.	S differ.	Dry weight grams
IIB1	370.4	1.26	369.1	10.1	2.9	7.2	392.8	68.8	324.0	129.4	71.2	58.2	5.6	20.8		391.3	38.4	352.9	2.71
IIB2	370.4	1.08	369.3	29.8	2.3	27.5	392.8	57.6	335.2	129.4	45.6	83.8	18.3	52.8		391.3	36.8	354.5	3.82
IIB3	370.4	.81	369.5	54.3	3.1	51.2	392.8	60.8	332.0	129.4	61.0	65.4	34.1	20.8		391.3	33.4	357.9	4.11
IIB4	370.4	.90	369.5	251.1	7.5	243.6	392.8	67.2	325.6	129.4	62.8	66.6	161.0	44.8	116.2	391.3	28.0	363.3	9.30
IIB5	370.4	1.35	369.0	497.1	8.6	488.5	392.8	86.4	306.4	129.4	64.0	65.4	319.7	41.6	278.1	391.3	29.6	361.7	7.76
IIC1	246.9	.63	246.3	10.1	3.1	7.0	303.0	72.0	231.0	113.7	48.4	65.4	5.6	44.8		297.2	32.9	264.3	2.73
IIC2	246.9	.90	246.0	29.8	2.3	27.5	303.0	70.4	232.6	113.7	56.8	56.9	18.3	70.4		297.2	27.4	269.8	3.22
IIC3	246.9			54.3	3.4	50.9	303.0	52.8	250.2	113.7	71.2	42.5	34.1	13.6	20.5	297.2	51.6	245.6	8.20
IIC4	246.9	.54	246.3	251.1	6.5	244.6	303.0	46.4	256.6	113.7	56.8	56.9	161.0	57.6	103.4	297.2	42.2	255.0	8.66
IIC5	246.9	1.39	245.5	497.1	7.5	489.6	303.0	33.6	269.4	113.7	74.0	39.7	319.7	24.8	294.9	297.2	19.7	277.5	7.88
IID1	123.5	.45	123.0	10.1	2.3	7.8	168.3	56.0	112.3	90.0	51.2	38.8	5.6	24.0		156.2	19.4	136.8	2.47
IID2	123.5	.81	122.7	29.8	2.6	27.2	168.3	32.0	136.3	90.0	56.8	33.2	18.3	12.8	5.5	156.2	19.4	136.8	5.83
IID3	123.5	.76	122.7	54.3	3.4	50.9	168.3	20.8	147.5	90.0	60.8	29.2	34.1	9.6	24.5	156.2	27.4	128.8	6.27
IID4	123.5	.45	122.0	251.1	3.6	247.5	168.3	38.4	129.9	90.0	78.0	12.0	161.0	8.0	153.0	156.2	20.8	135.4	7.60
IID5	123.5	.45	122.0	497.1	5.8	491.3	168.3	37.6	130.7	90.0	79.6	10.4	319.7	17.6	302.1	156.2	8.2	148.0	6.75
IIIA1	493.9	1.8	492.1	300.3	4.6	295.7	38.1	16.4	21.7	160.9	49.6	111.3	192.8	12.0	180.8	143.0	10.9	132.1	4.65
IIIA2	493.9	3.6	490.3	300.3	4.6	295.7	56.0	28.0	28.0	160.9	74.0	86.9	192.8	7.2	185.6	158.2	33.4	124.8	7.88
IIIA3	493.9	2.7	491.2	300.3	6.5	293.8	78.6	22.0	56.6	160.9	61.2	99.7	192.8	19.2	173.6	171.5	24.6	146.9	6.97
IIIA4	493.9	2.3	491.6	300.3	6.0	294.3	258.0	57.6	200.4	160.9			192.8	21.6	171.2	322.9	60.4	262.5	10.53
IIIA5	493.9	2.3	491.6	300.3	7.3	293.0	483.6	29.6	454.0	160.9	71.2	89.7	192.8	17.6	175.2	455.9			8.11
IIIB1	370.4	3.61	366.8	207.9	6.0	195.9	38.1	26.4	11.7	129.4	35.6	93.8	129.3	10.4	118.9	101.6	15.6	86.0	8.18
IIIB2	370.4	2.25	368.1	207.9	6.2	195.7	56.0	40.0	16.0	129.4	68.4	61.0	129.3	23.2	106.1	116.8	38.9	77.9	5.87
IIIB3	370.4	1.35	369.0	207.9	5.8	196.1	78.6	24.0	54.6	129.4	49.6	79.8	129.3	10.4	118.9	129.1	36.9	92.2	8.84
IIIB4	370.4	1.44	368.9	207.9	5.8	196.1	258.0	43.2	214.8	129.4	99.6	29.8	129.3	4.8	124.5	281.5	10.2	271.3	4.86
IIIB5	370.4	.85	369.5	207.9	5.0	196.9	483.6	67.2	416.4	129.4	96.6	32.6	129.3	8.0	121.3	414.5	59.8	344.7	8.82
IIIC1	246.9	.36	246.5	152.8	2.9	149.9	38.1	28.0	10.1	113.7	82.8	30.9	97.6	8.0	89.6	80.7	17.5	63.2	6.58
IIIC2	246.9	1.58	245.3	152.8	4.4	148.4	56.0	18.4	37.6	113.7	75.2	38.5	97.6	8.8	88.8	95.9			8.57
IIIC3	246.9	.77	246.1	152.8	3.8	149.0	78.6	35.2	43.4	113.7	91.2	22.5	97.6	7.2	90.4	109.2	28.5	81.7	9.40
IIIC4	246.9	.41	246.5	152.8	7.0	145.8	258.0	41.6	216.4	113.7	62.8	50.9	97.6	10.4	87.2	260.6	50.0	210.1	7.66
IIIC5	246.9	4.52	242.4	152.8	7.3	145.5	483.6	60.8	422.8	113.7	84.0	45.3	97.6	11.2	86.4	393.6	30.7	262.9	8.68
IIID1	123.5	4.52	118.9	79.0	5.8	73.2	38.1	18.4	19.7	90.0	48.4	41.6	50.0	7.2	42.8	49.5	28.0	21.5	5.56
IIID2	123.5	4.06	119.4	79.0	4.1	74.9	56.0	18.4	37.6	90.0	85.6	4.4	50.0	6.4	43.6	54.7	23.0	31.7	7.29
IIID3	123.5	3.16	120.3	79.0	6.0	73.0	78.6	17.6	61.0	90.0	68.4	21.4	50.0	9.6	40.4	78.0	19.7	58.3	6.96
IIID4	123.5	4.52	118.9	79.0	6.5	72.5	258.0	40.0	218.0	90.0	89.2	.8	50.0	7.2	42.8	229.4	29.1	200.3	6.75
IIID5	123.5	4.96	118.5	79.0	6.0	73.0	483.6	48.0	435.6	90.0	84.0	6.0	50.0	3.2	46.8	362.4	45.0	317.4	6.36

in either of the other series, a result which is explicable since nitrogen is a more important limiting factor than phosphorus, and phosphorus is in turn more important as a limiting factor in growth than potassium. Hence in a solution where nitrogen is deficient, and potassium and phosphorus present in optimum amounts, a smaller crop production results than is the case where phosphorus is the deficient factor. A deficiency of potassium does not so seriously affect the intake of other salts, with the result that a better crop is produced than is the case where phosphorus is the deficient factor.

The method of analysis which it was necessary to use makes the analytical values for phosphorus and magnesium rather unreliable. In series II, where phosphate was added in increasing quantities from pot 1 to pot 5 in each group, the analysis of the water extract shows the effect of this increment. It will be noticed that the analytical values are all of about the same order of magnitude, which may point strongly to adsorption by the sand. No general conclusion as to the adsorption of phosphorus and of magnesium can be drawn for the reasons above enumerated.

In the case of potassium the method of analysis was much more accurate. There is evidence in series I, groups A, B, C, and D, of an increase in the amount of potassium absorbed which in general seems to be related to the more vigorous growth resulting from the increasing quantities of nitrogen as added in these groups. A similar relation holds in the other two series, as will be seen from the ratios between potassium added and potassium remaining, which are higher where the nitrogen is added in large quantities than is the case where this element was present in small quantities. The high ratios of potassium added to potassium remaining after growth, therefore, usually occur where the dry weight is highest.

Not much can be said on the absorption of calcium. In series I it is noticeable that the quantity of calcium remaining, as compared in the four groups of this series, bears an inverse relation to the calcium added. Less calcium is absorbed from the solutions of low total concentration than from those which have a high concentration. Since the crop production was

greater in group D, the calcium must have been used with greater economy in this group where the total concentration was low.

The large number of variables which are present in each of the solutions make accurate deductions concerning the exact relation between any element and the growth of the plant almost impossible. In fact, growth has been shown to be influenced not by one factor alone but by combinations of factors.

GENERAL DISCUSSION

It is evident, as noted above, that the large number of variables present in an experiment of this character so complicates the situation that definite conclusions are drawn only with considerable difficulty. Inorganic salts can be used by the plant only from solution. The complexity of this solution increases with the number of ions, which must be rather large since the plant cannot make normal growth unless certain ions are present. To further complicate the situation, all the salts may be available which are required for growth, but the unbalanced condition of the solution may cause injury to the growing plant.[34] This condition of balance, in turn, seems to be related to the total concentration of the solution as well as to its qualitative composition.[35] In this connection it is important to note that if it were possible to keep the balance in the solution constant by renewal of salts, growth differences would be less marked than when the plant grows in a solution in which the balance is constantly changing due to absorption of ions by the plant.[36] All of the above points must be taken into consideration in any experimental work which is done in this field of investigation. The exact influence which the concentration of the solution has upon the complicated physiological processes concerned in plant nutrition is a problem which can be solved only by the gradual accumulation of a mass of evidence bearing upon the subject. The complexity of the whole problem is such as to require more than

[34] Loeb, Archiv. ges. Physiol., vol. 88, pp. 68–78, 1902, and Amer. Jour. Physiol., vol. 3, pp. 327–338, 1900; Osterhout, Science, n. s., vol. 35, pp. 112–115, 1912, and Jour. Biol. Chem., vol. 1, p. 363, 1906.

[35] Gile, *loc. cit.*

[36] Brenchley, Ann. Bot., vol. 30, pp. 77–90, 1916.

the evidence of a single set of experiments for proof. The evidence presented by the work herein reported is an addition to that already reported by other investigators, who have shown that the absorption is influenced to a more or less marked degree by the concentration of the solution. Conclusions which have been reached in regard to the effect of certain variables in this study must be understood to apply only in the case of the specific combinations of salts studied, and in connection with the growth of the tobacco plant in sand cultures.

SUMMARY

Results are above given which deal with the influence of the composition and concentration of the nutrient solution on sixty different plants of an F_1 species-hybrid of *Nicotiana*.

1. 2000 g. of washed sand of known composition was used as a culture medium for each plant.

2. The salts used were $NaNO_3$, $Ca(H_2PO_4)_2$, K_2SO_4, and $MgSO_4$.

3. The salts were so distributed as to give at least three important variables: first, as to a single nutrient salt; second, as to total concentration of salts; and third, as to the balance of salts in the solution.

4. The influence of the solution on the growth of the plant was judged by the following criteria: height, leaf length, leaf width, flower production, dry weight of tops.

5. Nitrogen is a more important growth-limiting factor than phosphorus, and phosphorus is, in turn, more important in this capacity than potassium.

6. The total concentration of the solution has a marked influence upon growth. Plants growing in solutions of low concen-

tration were in general superior to those grown in solutions of higher concentration.

7. Flower yield as well as vegetative vigor is influenced by the composition and concentration of the nutrient solution.

8. The physiological balance of salts in the solution is an important factor which must be taken into consideration in connection with the composition and concentration of the solution. Growth is influenced by a combination of all of these factors.

9. A quantitative analysis of the sand used in each pot was made after the plants were harvested.

10. Evidence of adsorption is seen in the results of the quantitative analysis of the water extract from the sand.

11. The concentration of the nutrient solution clearly affects the economical use of nitrogen.

12. High ratios of potassium added to potassium remaining after growth usually occur where the dry weight production is greatest.

13. Less calcium is absorbed from solutions of low total concentration than from those which have a high total concentration.

14. Calcium seems to be used with greater economy in solutions where the total concentration is low than in solutions in which the total concentration is high.

Transmitted April 21, 1916.

PLATE 5

TREATMENT

	NaNO$_3$ Grams	Ca(H$_2$PO$_4$)$_2$ Grams	K$_2$SO$_4$ Grams	MgSO$_4$ Grams	Total Grams
Pot 1D1	.02	.3	.6	.24	1.16
Pot 1D2	.2	.3	.6	.24	1.34
Pot 1D3	1.0	.3	.6	.24	2.14
Pot 1D4	2.0	.3	.6	.24	3.14
Pot 1D5	3.0	.3	.6	.24	4.14

PLATE 6

TREATMENT

	NaNO$_3$ Grams	Ca(H$_2$PO$_4$)$_2$ Grams	K$_2$SO$_4$ Grams	MgSO$_4$ Grams	Total Grams
Pot IA4	2.0	1.2	2.4	.96	6.56
Pot IB4	2.0	.8	1.6	.64	5.04
Pot IC4	2.0	.6	1.2	.48	4.28
Pot ID4	2.0	.3	.6	.24	3.14

PLATE 7

TREATMENT

	NaNO₃ Grams	Ca(H₂PO₄)₂ Grams	K₂SO₄ Grams	MgSO₄ Grams	Total Grams
Pot 1C1	.02	.6	1.2	.48	2.30
Pot 1D3	1.0	.3	.6	.24	2.14
Pot 1B1	.02	.8	1.6	.64	3.06
Pot 1D4	2.0	.3	.6	.24	3.14
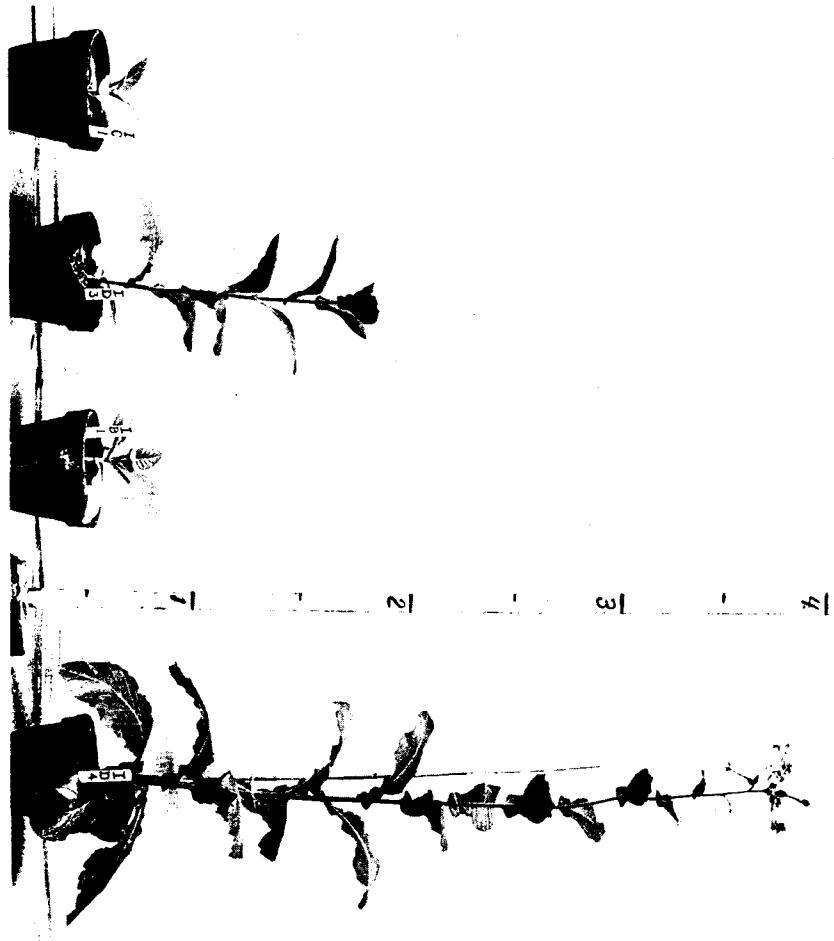
PLATE 8

TREATMENT

	NaNO$_3$ Grams	Ca(H$_2$PO$_4$)$_2$ Grams	K$_2$SO$_4$ Grams	MgSO$_4$ Grams	Total Grams
Pot IIB1	2.25	.02	1.6	.64	4.51
Pot IIB2	2.25	.1	1.6	.64	4.59
Pot IIB3	2.25	.2	1.6	.64	4.69
Pot IIB4	2.25	1.0	1.6	.64	5.49
Pot IIB5	2.25	2.0	1.6	.64	6.49
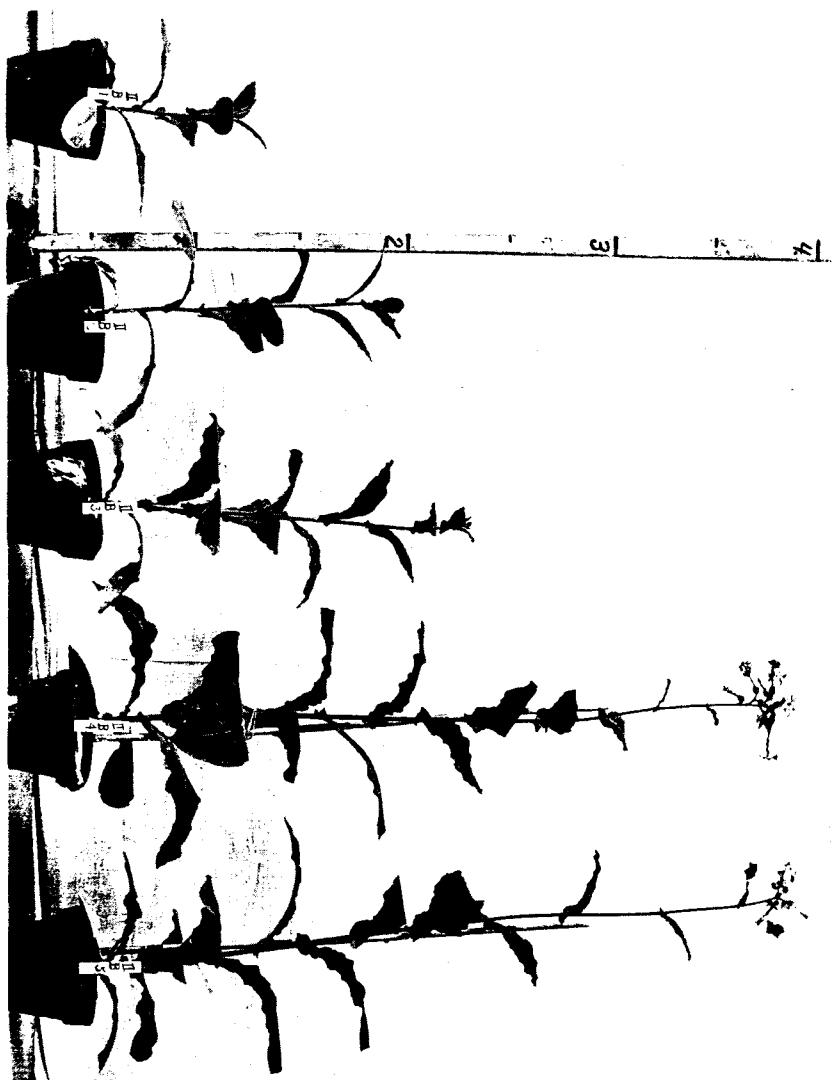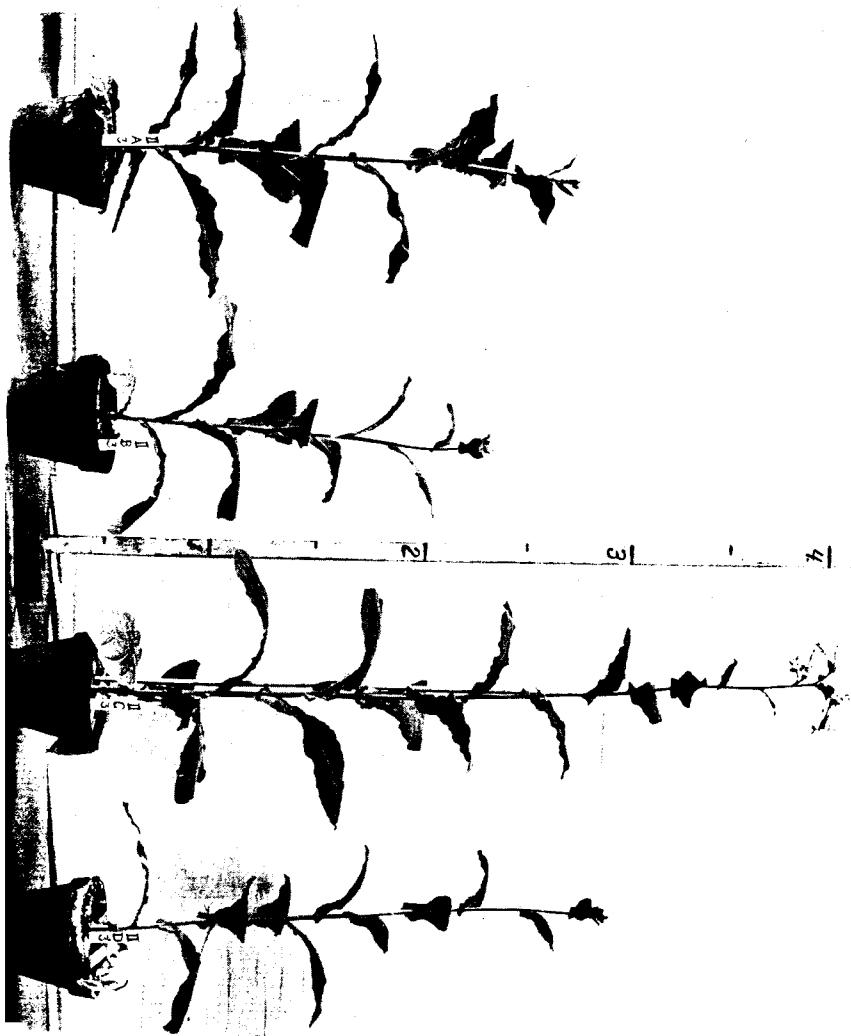
PLATE 10

TREATMENT

	NaNO$_3$ Grams	Ca(H$_2$PO$_4$)$_2$ Grams	K$_2$SO$_4$ Grams	MgSO$_4$ Grams	Total Grams
Pot 11C1	1.5	.02	1.2	.48	3.20
Pot 11C3	1.5	.2	1.2	.48	3.38
Pot 11B1	2.25	.02	1.6	.64	4.51
Pot 11B4	2.25	1.0	1.6	.64	5.49
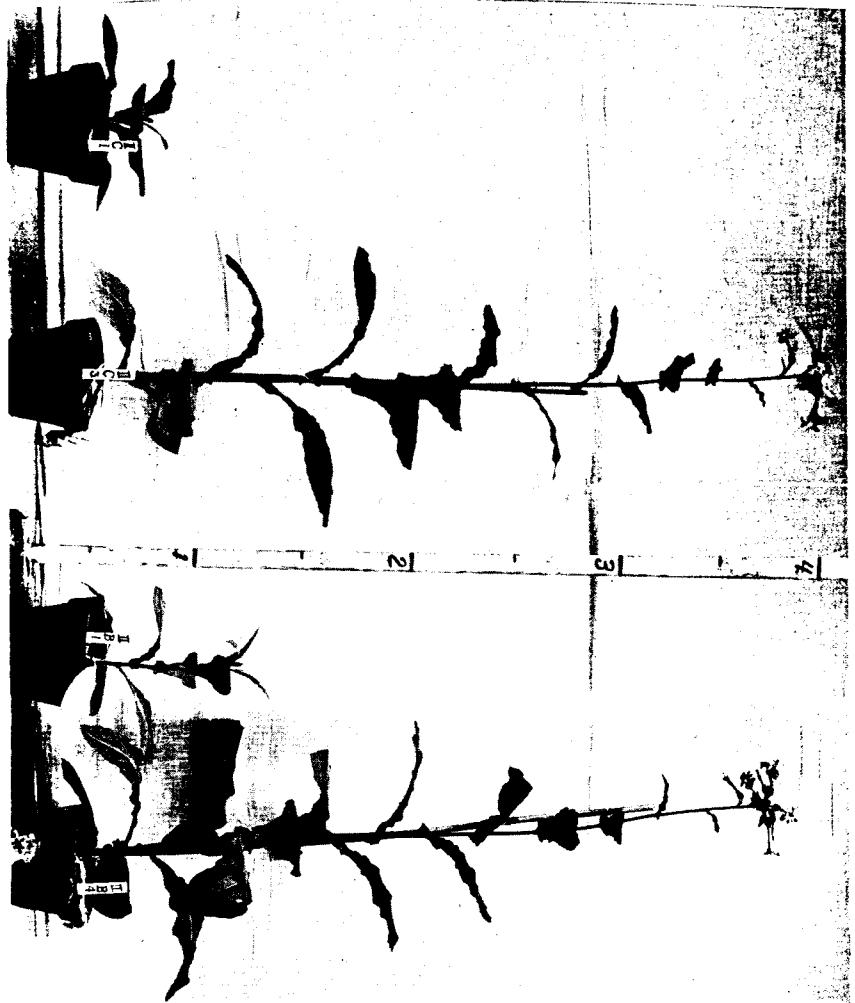
PLATE 11

TREATMENT

	NaNO$_3$ Grams	Ca(H$_2$PO$_4$)$_2$ Grams	K$_2$SO$_4$ Grams	MgSO$_4$ Grams	Total Grams
Pot IB3	1.00	.8	1.6	.64	4.04
Pot IIB3	2.25	.2	1.6	.64	4.69
Pot IIIB3	2.25	.8	.2	.64	3.89

PLATE 12

TREATMENT

	NaNO$_3$ Grams	Ca(H$_2$PO$_4$)$_2$ Grams	K$_2$SO$_4$ Grams	MgSO$_4$ Grams	Total Grams
Pot IIID1	.75	.3	.02	.24	1.31
Pot IIID2	.75	.3	.1	.24	1.39
Pot IIID3	.75	.3	.2	.24	1.49
Pot IIID4	.75	.3	1.0	.24	2.29
Pot IIID5	.75	.3	2.0	.24	3.29
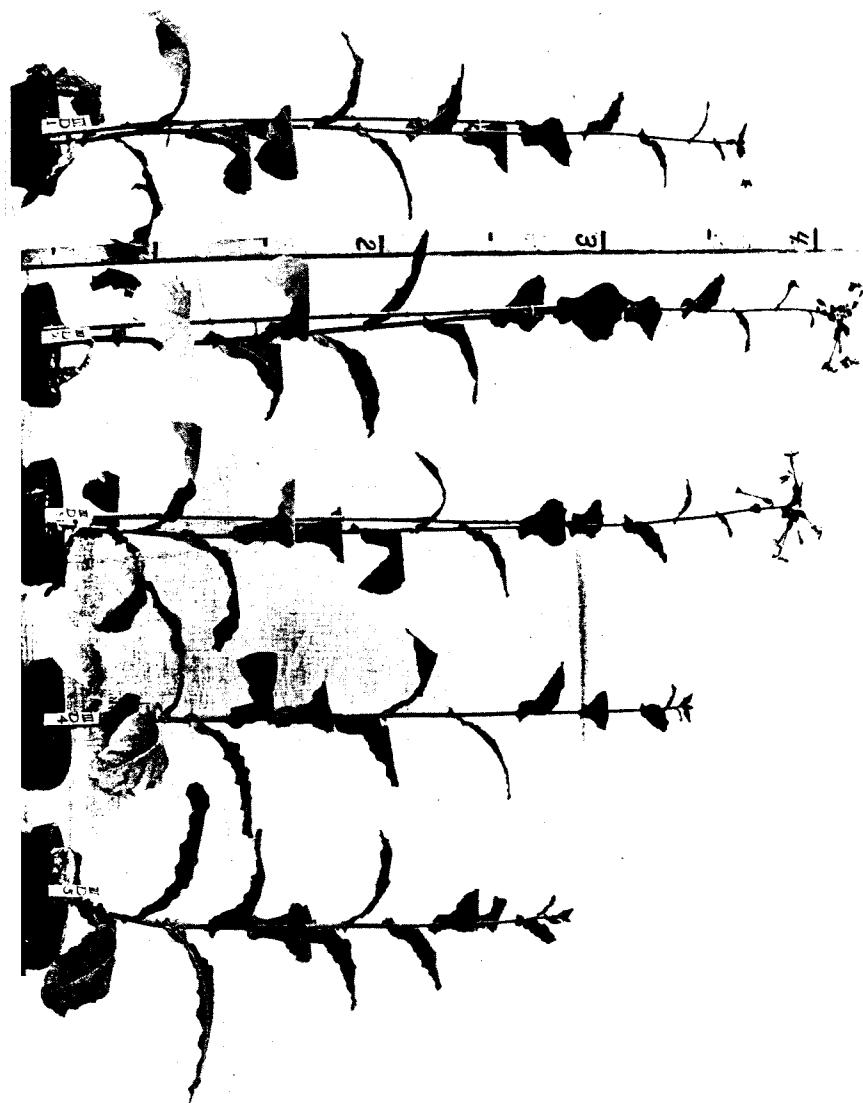
PLATE 13

TREATMENT

	NaNO₃ Grams	Ca(H₂PO₄)₂ Grams	K₂SO₄ Grams	MgSO₄ Grams	Total Grams
Pot IIA1	3.00	1.2	.02	.96	5.18
Pot IIIB1	2.25	.8	.02	.64	3.71
Pot IIIC1	1.5	.6	.02	.48	2.60
Pot IIID1	.75	.3	.02	.24	1.31
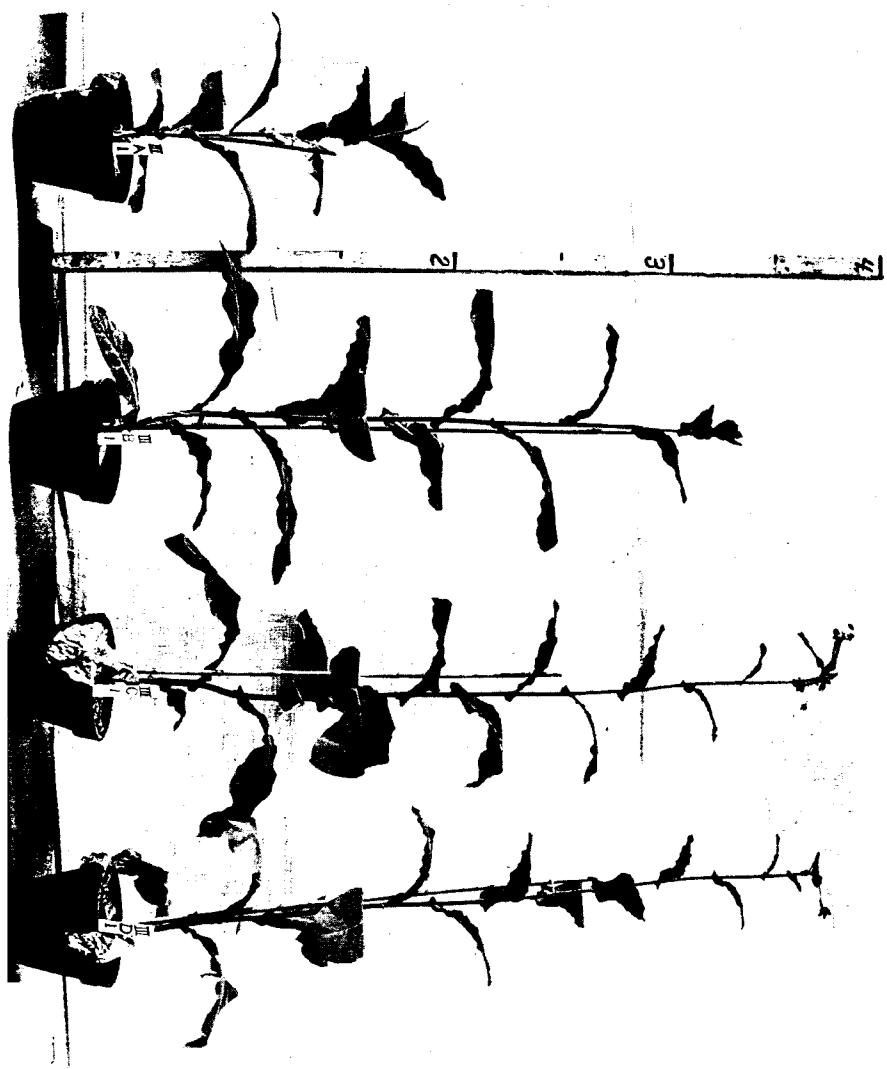
PLATE 14

TREATMENT

Plant growing in washed sand
Plant growing in soil

	NaNO$_3$ Grams	Ca(H$_2$PO$_4$)$_2$ Grams	K$_2$SO$_4$ Grams	MgSO$_4$ Grams	Total Grams
Pot IIIB2	2.25	.8	.1	.64	3.79

PLATE 15

TREATMENT

	NaNO$_3$ Grams	Ca(H$_2$PO$_4$)$_2$ Grams	K$_2$SO$_4$ Grams	MgSO$_4$ Grams	Total Grams
Pot ID2	.2	.3	.6	.24	1.34
Pot IID2	.75	.1	.6	.24	1.69
Pot IIID2	.75	.3	.1	.24	1.39